Rocket Propulsion

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Lecture No # 22

Introduction to Solid Propellant Rockets

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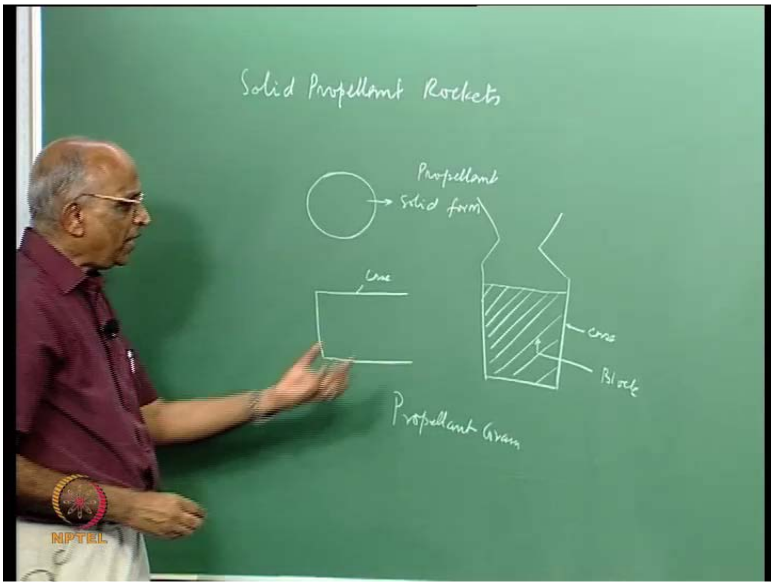

Well, good morning. Now, today we will start on solid propellant rockets and this will be an extremely simple topic may be we say, we will take a look at what are the elements of a solid propellant rocket, but primarily, we start from the propellant point of view, because that is what we have covered so far. We told ourselves solid propellant propellants consists of may be double based, may be composite, may be composite modified double base, and also we said nitramine propellants. Whenever these propellants are there, you have may be some base in which you cure the substances, you make it into something like a solid form, and this solid is what constitutes let us say a solid propellant, and we would like to use it to generate thrust.

Therefore, what is it we do, we take let us say a case could be a cylinder may be I put the propellant inside the case how do you put it inside the cylinder or a case? We say a case, which may be a cylinder in which, I want to keep the propellant in may be what I do is I keep the case vertically, I put all the ingredients into it I make it into a sort of a liquid or a slurry, then I cure it and I get something like a solid which is formed over here and then, I attach a nozzle to it and this becomes my solid propellant rocket.

Therefore, in a solid propellant rocket I have something like a structural member which is a case in which either, I pour the slurry of the mixture may be a composite slurry consisting of the binder may be the ammonium per chlorate and aluminum in into in this. Then I take it into a furnace I make sure I cure it I cure it at a temperature of between 70 to 200 depending on the composition, I form a block may be a composite solid propellant block which we call as a propellant grain. And when I cure or I put the slurry or the mixture in it and make it as a solid inside a case the rocket or solid rocket is known as a case bonded.

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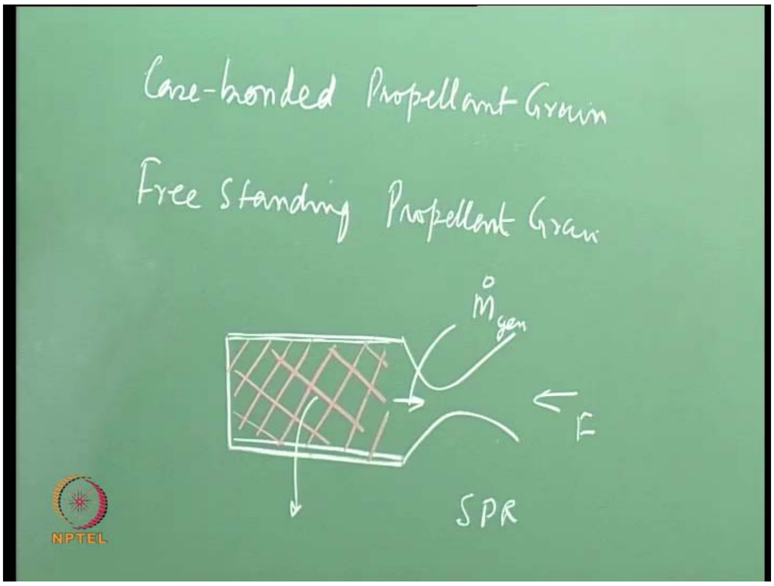

Case-bonded Propellant Grain

Free Standing Propellant Grain

It is also possible to make the propellant in the form of a paste and extrude it out just like we squish out the tooth paste from it is container. We could thereafter cure this squished out paste using in a in a furnace and enclose it in within a heat and then I charge it into the case in which case, it is known as a free standing. And what is free standing? The grain propellant inside it is free standing it is known as a free standing propellant grain or it is known as a case bonded propellant grain. Therefore, without any adieu I have just introduced the word grain what does grain mean, the propellant block which is put of a particular configuration in a case is what we call as a grain this grain or propellant grain could either be directly cured in the case itself in which case it is known as case bonded.

And when it is cured outside and maybe I will machine it and then push it into the case the propellant grain is known as free standing, we have both the things being operational, but when we talk of large solid propellant rockets invariably we cast it in the case itself. But there are certain more things as the propellant burns the hardware or the metal case or whatever be the case will get heated therefore, it is necessary for us, if I have a case I have something like a liner and this liner could be an insulator and then I put the propellant into it may be I say the propellant I put in into it and then I attach a nozzle onto it.

Therefore, I have a case may be an insulator or something which will which will make sure that when something burns the hot gases do not come and melt the motor case or the case as it where and then I have the nozzle and this what constitutes the solid propellant rocket. But what is it we want a rocket to do we want the rocket essentially to generate some thrust, in other words I say the thrust of the rocket is equal to m dot into V J or m dot into the specific impulse. We learnt how to calculate the specific impulse and supposing I want to generate a large force, I want to generate more mass flow from the burning propellant.

Therefore, in today’s class we will first examine how do you make a grain a propellant grain which could either be one of the two case bonded or free standing from which, if I ignite it start burning it how do I ensure that I have sufficient amount of mass getting generated from the propellant. We have just studied the chemistry of the propellants, but we have not studied anything about how it will burn I want to get some feel for how a propellant surface will burn and how do I calculate the mass generation rate and what should be the surface area such that I get the concerned thrust and this is what I will be talking today.

Let us again look at the problem in a slightly different scenario, but before that to repeat here if I have a composite propellant like I have something like a polybutadiene which is a resin. I put the resin which is a liquid form I put into it the solid loading crystals a p and aluminum I have a slurry a mixture of all these things, I heat it to a high temperature from a solid block and this solid block when it is inside a case is what is known as a propellant grain. And what is this resin is something when heated it sets and this resin is known as thermosetting resin, because when heated it becomes hard resin is nothing but a polymer polybutadiene like glue.

I will show you some example may be, but if you have plastic which is also a resin when I heat it softens therefore, we cannot use such resins for composite propellants and the same thing is true when I use nitrocellulose and nitroglycerine I make it as a liquid I cure it I make it as a block and this block is known as a propellant grain. Therefore, we are interested in finding the burn rate the rate at which it will burn the rate at which mass gets generated from a grain is it clear, we must differentiate between a propellant block that is a hard propellant which is which is got after curing.

May be a propellant grain is a particular grain which gives me a given area through which I generate M dot generated hot gases may be I have to still address this problem that is what is known as propellant grains. And this propellant grains could either be directly bonded in a case or the hardware of a rocket or it could be done elsewhere, just you inside the case in which case it is known as free standing the other one is known as case bonded.

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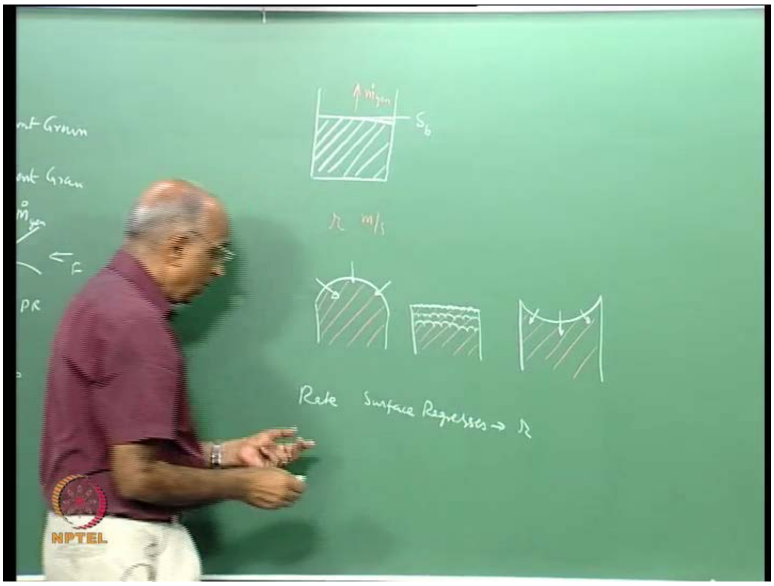

I think this is all about the terminologies now, let us get back and ask ourselves if I have a surface let us say I have a case over here, I put the propellant block inside it and let us say I have no nozzle at all this is my propellant. I want to generate hot gases may be this is the surface area of my propellant I call it as burning surface area I call it as s b. Supposing this surface is ignited I would like to know a rate at which I am generating the hot gases from it. And therefore, what is required? I must know the rate at which the propellant regresses or burns in other words I would like to you have something like r so, many meters per second is the rate at which a propellant burns what is this rate let us spend some time on it.

Supposing, I have a surface which is like this let us say a convex surface and this is let us say the propellant over here or these other example I can take is a flat surface of a propellant, which is the propellant is over here. Or the other extreme is I take a concave surface something like this and this is my propellant over here, I could have different configurations or I could have whole right through. Let me consider these cases when I start burning at the surface over here, at the next instant the flame comes over here and then it comes over here.

In other words the burning progresses into the propellant as it burns it more and more and the rate at which the surface regresses is what we call as the burning rate. Rate at which surface regresses, but it must be normal to the surface and that is why I made these drawings over here the surface regresses in this direction over here the surface regresses in this direction over here surface regresses in this direction. Whereas, in this case the surface normal to it is what constitutes the burning therefore, we call burning rate as something normal to the surface.

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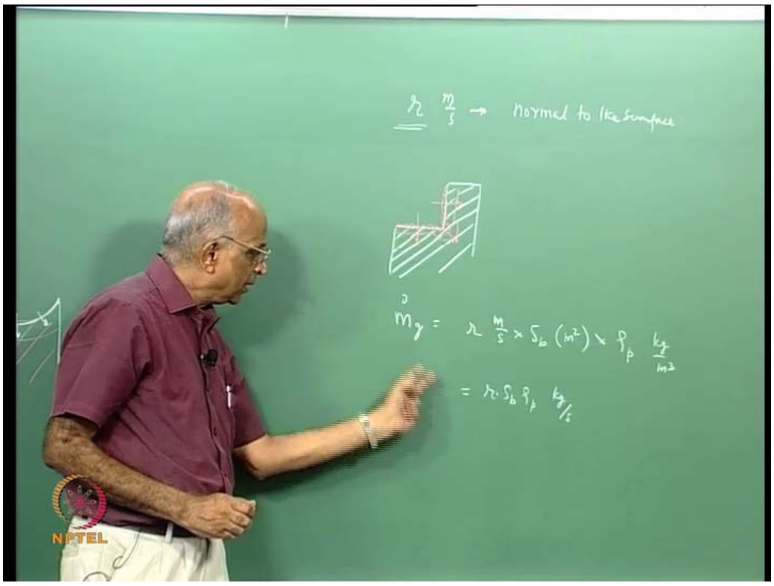

When I say a propellant burns at the rate r meters per second, I assume that the burning is normal to the surface. Let us spend some more time on this supposing I have a propellant let us say a block something like this, this is my propellant. Let us say now, I have the propellant in this configuration may be this is my propellant here and now I ignite or I start burning over here and over this surface how will the burning take place? The burning will take place normal to this surface the burning will take place normal to this surface and what happens to this contact point well it should go like this right. In other words over here since it is normal to this point it will go as a circle over here it will go as a line and this is how normal to the surfaces how burning takes place. May be we will have to look at this in some detail when we come to different configurations of the propellant grain.

Therefore, we tell ourselves well for anything to take place I tell myself I define something like a burning rate in terms of meter per second which is normal to the surface and the gas generated rate of mass gas rate of mass which is generated by the burning is equal to let us say r is the burn rate so, many meters per second into let us say the burning surface area so, many meter square. This gives me meter per second into meter square which is meter cube per second that is the volume at which the volume rate at which the burning or the solid propellant gets consumed.

In other words the volume rate at which the regression takes place and then, I multiply it by the density of the propellant, which is so much kilogram per meter cube. I get meter cube meter cube gets cancel I get m g is equal to r into the burning surface area into rho p so, much kilograms per second. Therefore, the rate at which mass gets generated from a surface can be written in terms of the linear or the regression burn rate as burn rate. In terms of a linear dimension into the burning surface area in this case the whole thing is the burning surface area in this case.

The burning surface area is this and at the next instant of time may be it is over here this is the burning surface area this is the burning surface area and you have burning surface area into the burn rate into this and burn rate is nothing but the rate of regression of the surface. Therefore, we say mass generated by burning is equal to the burn rate in meters per second surface area in meter square density in kilogram per meter cube I think this part must be clear. Then let us illustrate it through an example, because we also you will recall we have been talking of black powder in the course on explosion explosions and there we said what does what did black powder consist of we said it consists of an oxidizer like.

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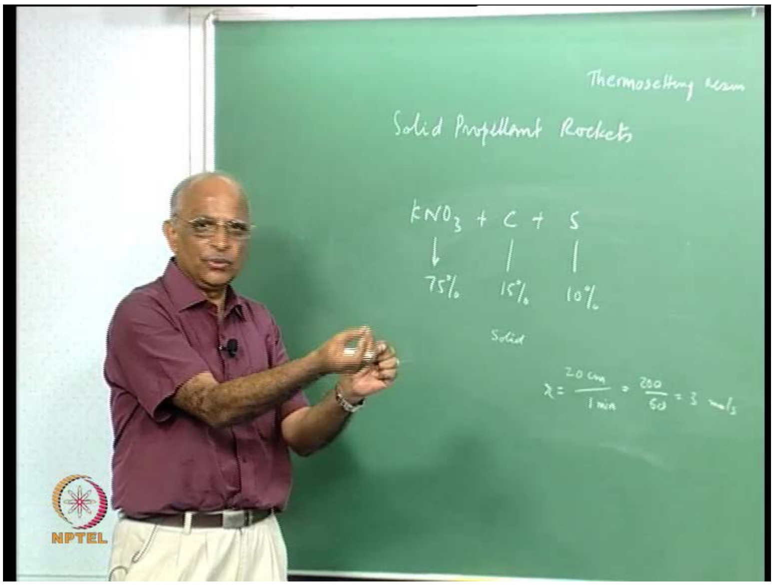

Let us say k N o 3 and it also consisted of something like charcoal you say carbon which is charcoal and some part of sulfur, we had said at that time that it consists of something like 75 percent potassium nitrate maybe something like 15 percent of carbon and sulfur is the remaining something like 10 percent. And how do you form these crackers or sparklers which use this black powder. You have these solids this is an oxidizer fuel and fuel you grind them together may be make a good mixture of it may be add some glue may be in that case it becomes wet. You sort of cure it make it as a solid and that is what constitutes a composition what we are telling well this is also a composite propellant.

Therefore, let us take the example just to understand a little bit further about burn rate I brought a sparkler with me may be we will take a look at it and we will see how we look at the burn rate of these devices. I will just ignite it I brought two sparklers, because I thought the effect of aluminum must also be clear to us let us just ignite it and see what happens (No audio from 15:30 to 15:38) well this is ignition right you ignite a candle. Well, this is a sparkler this consists of as I said the composition, and the composition is again carbon you have sulfur and you have k N O 3 and this is it is it will burn by itself it is a propellant and it is group together instead of using polybutadiene it has resin that is the glue that is gum which is used.

Well, you ignite it you ignite it at the surface, see you know how does burning take place you know you have this surface, which gets ignited and this ignited surface burns the next surface next surface and all that therefore, you will find that this surface is regressing at a particular rate. Well, in this case the whole surface is exposed, but because it is air over here the flame expanded it is not able to ignite this therefore, the burning surface area is perpendicular to this plane and the burning progresses. This is the case of this composition, while at this composition let us see what is the effect we have when we have something like a metal see in this sparkler, the same composition is used, but some iron filings are used some metal is added and if I have to ignite the metal.

(No audio from 17:00 to 17:26)

You see the distinct effect of the metal see the metal being metal having so much energy you find the heat which is much higher and that is why we say metal has a higher heat of combustion and that is why metals are prepared in solid propellant rocket. Again we are talking of the same thing the surface regressing as it is going on and we find that the propellant regresses it burns. And what is happening is something is getting ignited gas is getting generated the rate at which the surface is regressing is the rate at, which mass is getting generated and this is all about it.

You see the energetics you know the energetics is such that you know this falls on me I feel little warm, but this is harmless. Therefore, you find that metals have a definite role to play and I think this is all what I wanted to illustrate is you are talking of a burning rate which is linear. We will come back to our sparklers when we talk of combustion instability we will see how even this can make a cavity into unstable mode, but the purpose is there is something like a propellant it regresses and as it regresses mass gets generated and this is all what we say about burning rate.

Therefore, what will be the typical burning rate there we had a length something like almost twenty centimeters it burnt over a period of one minute therefore, the mean burn rate r is equal to 200 millimeters divided by 60, which is something like 3 M per second or so 3.3. And this is our burning rate is calculated you have precisely a solid propellant you make it you ignite it and that is what a burning rate. Therefore, with this background I think it is time to go ahead and examine the burn rate of let us say the double based propellants may be the composite propellants we will try to get into some details we will try to see whether, we can make some sense of what our composition was.

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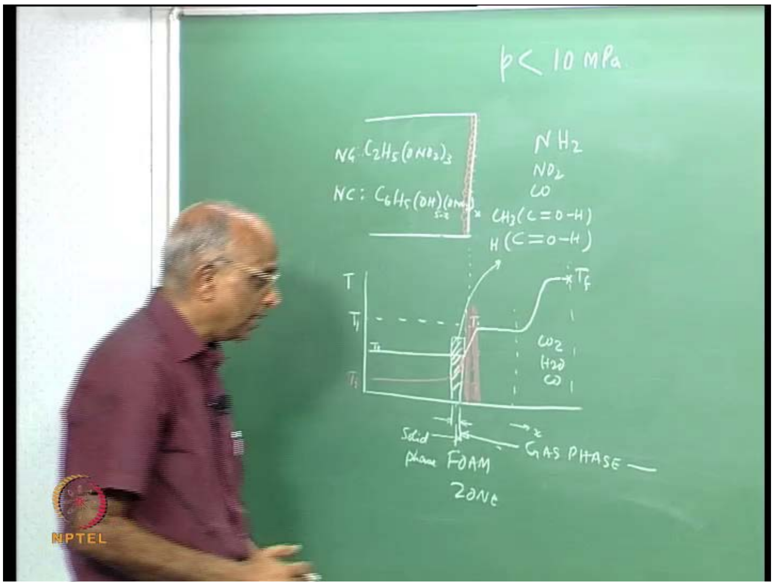

Let us say I have a double based propellant over here, and just the same way I ignited this sparkler I sort of ignite I put a fire over here or a heat source over here start igniting it in other words, I start igniting this particular surface with a heat source. What was the composition of double base? We told that it consist of may be nitroglycerine which is C

2 H 5 ONO 2 3 times it also had nitrocellulose this was nitroglycerine it had nitrocellulose and what was nitrocellulose we had C 6 H 5 OH and ONO2 what was done was. We had something like five of this we put x we removed x of OH and put ONO 2 there we had 5 minus x over here this was what we said is a double based propellant.

Now, I ignite the double based propellant and what happens may be a surface very near to the surface gets over heated, because all these propellants are all something like an insulator heat does not conduct deeply into it. And therefore, at the bottom, if I have had to considered this as the scale x along the distance and this is my surface over here; I say a small length or a small thickness of the propellant surface gets heated when I heat the surface. And therefore, my curve if this is my temperature axis on the y axis and this is my distance along will be something like this let me show it in red the depth is really not heated maybe it begins to get heated the temperature rises and here, I have the surface at the temperature T s and this is the original temperature.

Let us say the initial temperature of the propellant T I, all what I have done just like I ignited with a matchstick this sparkler. I ignite this particular surface and therefore, the surface temperature increases heat gets conducted over a certain thickness and thereafter the temperature is the original. These are all insulators I could have held the sparkler there, because the heat it is these are all insulators really does not conduct the heat.

Now, what happens when I heat this particular zone this particular zone begins to foam as it were begins to evolve some hot gases. And the gases which are evolved are essentially something like aldehydes which are C O H could be formaldehyde could be acetaldehyde c h three c o and h could be I could get some COI could get some NO2 these are the gases which are evolved. Because something is getting heated these gases tend to come out over here, and when this gases come out they react further; that means, I have a zone adjacent to the surface which is now at temperature T s which forms hot gases and the temperature continues to increase in this particular zone.

That means, adjacent to this particular zone of propellant which is getting heated which foams and forms hot gases this zone is known as foam zone that is the solid zone which is heated. And while it is getting heated it decomposes and generates these gases like aldehydes may be NO2 may be NO may be CO all these gases are coming they react and increase the temperature from, the surface temperature T s to a higher value of temperature which I call as T one this is the temperature T 1. These gases do not completely burn and when the pressure over here is less than, let us say something like 10 M P A that is about 100 bar.

What happens is the gases are not at very high pressure and they relax for some time they begin to mix you know it takes some time for the gases to burn and therefore, the temperatures remain at T 1 level for quite some time. That means, hot gases are generated it reacts increases the temperature from the surface temperature to T 1 and thereafter the gases are still reacting and what are the reactions which could take place? The reactions which could take place are something like C O which is formed here in addition to aldehydes even NH2 is formed may be C O plus NH2 reacts and like this you know may be CO and NO react, but these are not very exothermic reactions. And therefore, the temperature remains fairly constant till that time the ignition time that means, it is a precursor to the final reaction thereafter final reaction takes place and the final flame temperature is reached.

We have seen in the last class how to calculate the flame temperature using dissociative equilibrium using complete combustion I can calculate the flame temperature. But this flame temperature when the ambient pressure is less than ten M P A goes in steps initially it goes to T 1, then it mixes for sometime it reacts, but the reactions are not very exothermic and there after it increases this in this zone. Actually, CO2 H2O complete combustion products are formed and you get the maximum temperature of course, you have C O, because these are all fuel rich substances and therefore, you have something like a two step reaction processes are happening in the gas medium this is the gas phase.

This was the within the solid somewhere, no this was yes this was outside therefore, I should extend the gas phase right up to the boundary over here, this is the gas phase and this is the solid I will make it clear in the next diagram.

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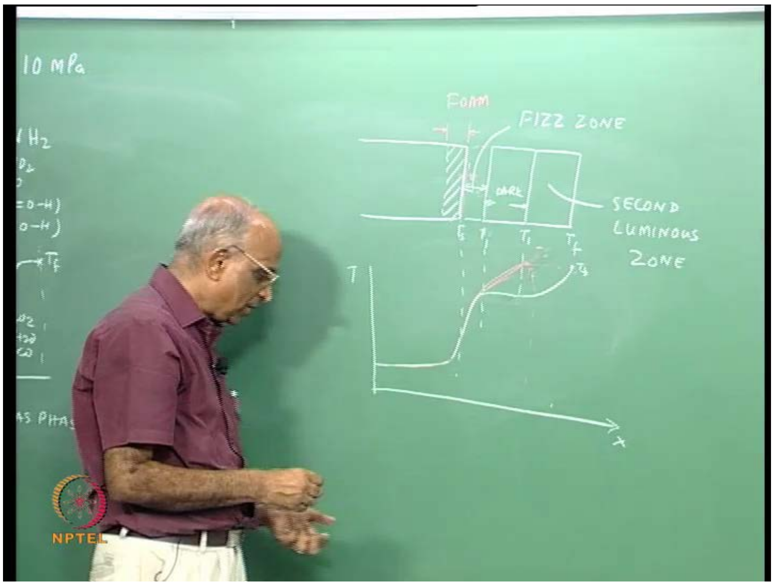

What is it I am talking of I am talking of a propellant solid block something like this; I tell that yes initially some amount of surface gets heated. And there after some chemical reactions are occurring in this zone and the temperature increases from the surface temperature to T f over here. Then I have another zone over here in which no increase in temperature we said T 1 I am sorry from T 1 it remains at T 1 over a certain zone and there after the final chemical reactions take place it leads to T f. Let us plot the temperature distribution again over here as a function of x, as a function of temperature over here.

We said at the surface this is the temperature starts from the initial value in this zone it increases, then it increases still further then, I have a zone in which the temperature is more or less constant and then the temperature shoots to the T f over here. This is the way a reaction takes place well this is all the gas part of it this is the solid part of it and it is this zone which we already called as foam zone f o a m. The zone in which the initial temperature increases in the gas phase is known as the fizz you know, because you are having some reactions zone it is known as fizz zone. This is very luminescent zone, because chemical reactions are happening just like we saw in this sparkler some luminosity this is very luminous zone and this is known as the fizz zone.

This is followed by a dark zone in which why it is dark nothing happens here, there is no further increase in temperature it looks dark and there after you have this zone which is the second luminous zone, because again high temperature comes second luminous zone. This is how a double base propellant when ignited burns to give you the high temperature T f, if I have very high pressures like exceeding 100 atmospheres that is 10 M P A what happens, because you have high pressure the chemical reaction continues or heat release continues here.

And I could have the temperature going straight away to T f over here, here itself it gets completed; that means, the dark zone will be absent when you have high pressure and you will have this luminous zone. First luminous zone followed by the second luminous zone straight it goes to the temperature final temperature which will be around the same value T f over here. That means, the temperature increases like this goes to the surface and then you have this zone and the temperature increases over here, this is at very high pressures whereas, at moderate pressures up to 100 atmospheres well you have this dark zone and then it increases.

Well, this picture should be sufficient for us to be able to calculate the burn rate what happens now? I have a high temperature T 1 over here from high temperature T 1 the surface temperature is lower heat gets conducted to the surface and it is this heat, which further heats this propellant surface and causes it to gasify and rigorous. Therefore, I am interested in events in the fizz zone wherein hot gases or heat from this zone gets conducted over here. In other words what is the model or what is my mental picture what I will have in mind see for us to do any problem it is necessary to first consider the physical problem. Like we say yes we look at the sparkler we looked at this we say yes regression takes place, we tell ourselves well heat is generated here.

The temperature in the fizz zone is T 1 heat gets conducted from T 1 to the surface and if I can calculate this heat which is conducted and then, I can write the equation at the surface and then get the burn rate this is my mental picture of the problem. The mental picture might be wrong if my mental picture is wrong the burn rate what I get might be wrong, but this seems to be reasonable this has been experimentally verified. But this thickness is what we are talking of even though I show it like this the total thickness of the fizz zone followed by dark zone followed by the second luminous zone is something like fraction of an m m, that means, it is all over here just like in the sparkler what happened in the sparkler.

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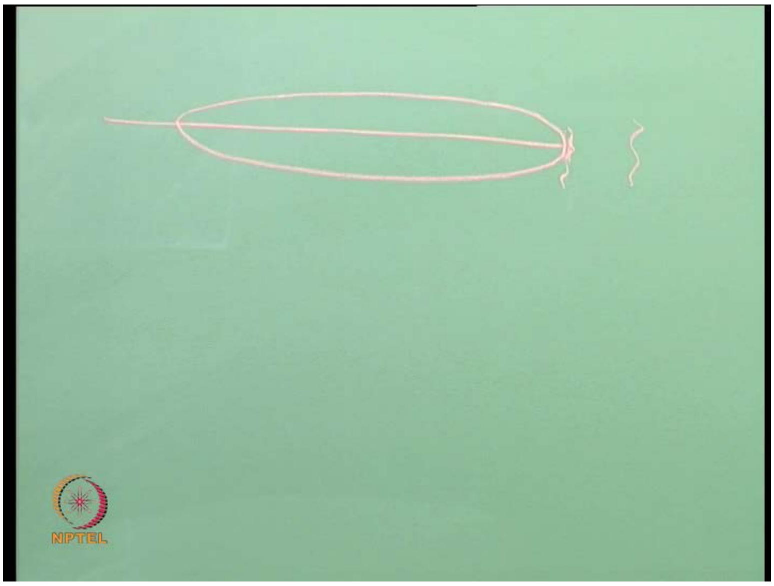

You had a rod you coated the propellant over here and what was this propellant k n o 3 plus carbon plus sulfur all bonded in it. We found right here itself gas is getting it is not that it is getting over here, the reaction distances are all within a fraction of an M even for that therefore, you can imagine we are talking of distances with a which are fraction of a millimeter thick.

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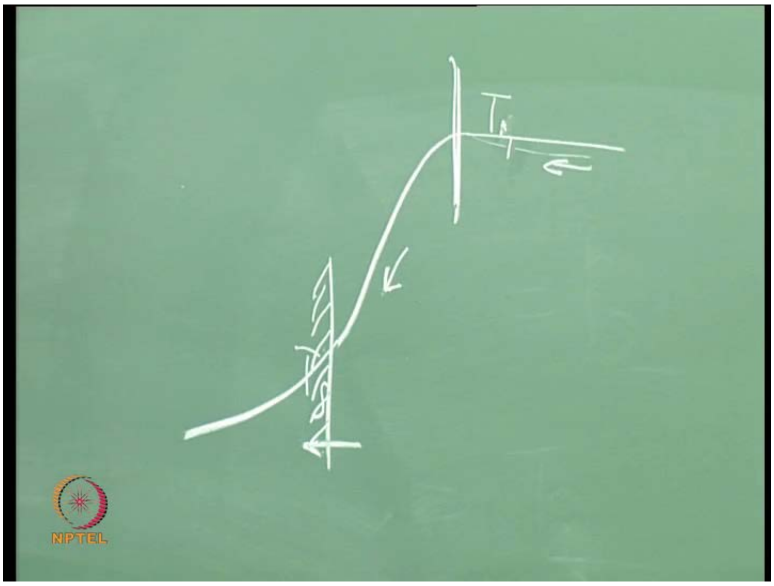

Therefore, let us write an equation for it and how do we write you know some it is not difficult at all. Well, now I say I have a surface I am going to be interested in the fizz zone, that is zone wherein temperature increases form T s to T 1, and then why am I not considering the dark zone. See the temperature is constant here, if temperature is constant here nothing is going to come over here only the from the hot zone let. If I were to say yes the temperature at the edge of the fizz zone is T 1 at the surface the temperature is T s I have T 1 to T s coming here and still coming down within the solid it is still decreasing.

I know that yes some heat is getting conducted along this, but in the dark zone since the temperature is constant no heat is getting conducted. Therefore, my condition here is T one over here, and the heat gets conducted from T one as the temperature falls I get some heat to be conducted and I would like to write the equation of what is going to happen at the propellant surface.

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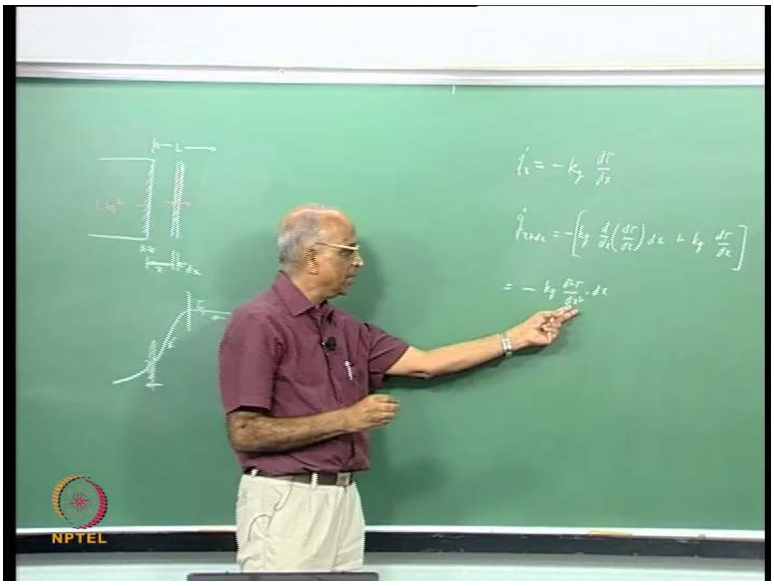

This is the mental picture or the model I have therefore, for this model let us write the equations. Well, I am interested only in the fizz zone let me forget about the dark zone and all that, I now say that let the length of the fizz zone be capital L, we recognize that we are talking of things which are fraction of a m thick. And I would like to concentrate let us say I have surface at x is equal to 0 this is the surface over here, I am interested in let us say a small element over here within the fizz zone at a distance x from the surface and of width d x.

I would like to write an equation for this element and then find out how the burning and this is how we do any heat transfer problem. Therefore, I am interested in finding out let us also to make things clear let me say that the surface area over here is equal to 1 unity 1 meter square such that I do not need to carry the value of a as I am doing the problem. Now, the temperature increases the let us say there is some heat conduction here what is the value of heat conduction q at x rate of heat conduction at x is equal to minus it is a gas phase therefore, thermal conductivity of the gas into dT by dx by Fourier law, q dot at x plus dx is equal to minus k g into now, I have d by dT of dT by d x.

I am sorry d by dx over the small increment into dx at x plus dx and therefore, but here this is the increment plus the value k g into dT by d x. And the net heat, if I were to consider this why not say I will consider this finite volume or consider this as the control volume. The net heat which is leaving this is equal to minus k g into d two T by dx square into dx is the net difference between the heat which is entering. Heat which is entering is equal to k g dT by dx heat which is leaving is k g dT by dx plus a small increment, which is d by dx into dT by dx into d x. Therefore, the net accumulation of heat in a controlled volume is equal to minus k g d 2 T by dx square into d x.

I think us we should learn to write these equations at any time for any problem, we will again be coming to these things and let us make sure we are clear, because when we want to ignite we must know how much ignition energy is there required. And therefore, we must learn to do these things, when burning takes place at the surface I think I will erase this part in the fizz zone we said temperature is increasing let the rate of chemical reaction heat release is equal to q dot chemical. So much let us say joules per let us say per volume this is joules per meter cube is the rate at which heat is getting generated. And therefore, the amount of heat which is getting generated in this volume is going to be q dot chemical into the volume of this element, and volume of this element is unit area into dx which is equal to q chemical into dx is the rate at which heat is getting generated in this volume.

Is there anything else I have to consider in a heat balance, we are telling ourselves well the propellant is burning consider the surface to be the frame of reference. With respect to this surface propellant is burning let us say at a value r what happens when the propellant burns hot gases are getting generated. Let the gases be moving let the gas moves at a velocity u g and this u g will be different from r, because r is for a solid u g is for a gas let the gases, let the mean density of the gases here be rho g therefore, the mass flow rate at.

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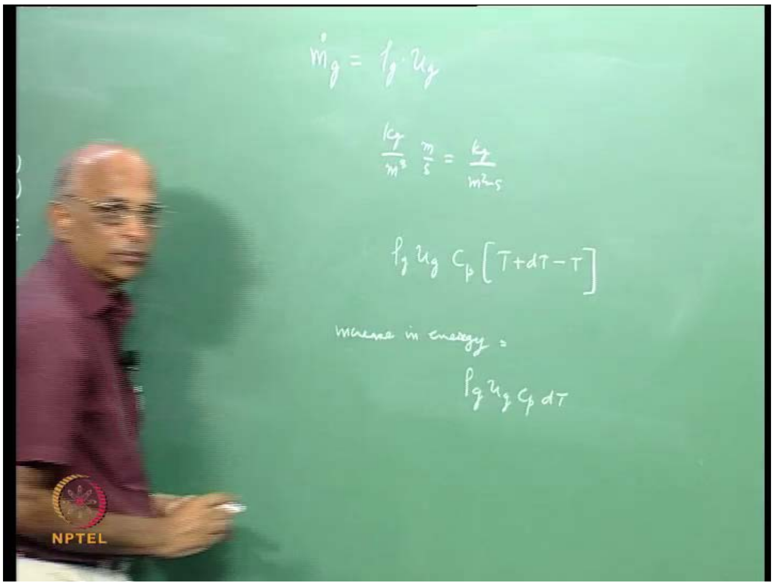

Which the gases are entering into this control volume is equal to m dot g per unit area I am taking therefore, I have rho g into u g that means, I have so much kilogram per meter cube into meter per second therefore, I have so much kilogram per meter square second. And since I am considering unit area the rate at which gas is moving or the mass flux is equal to rho g into u g and what is the enthalpy that is getting, gained as it moves through.

The gas is moving let us say this particular temperature here is T the temperature here at the next instant of time at x plus dx is equal to T plus d T, because there is a small increase in temperature. And therefore, the increase in enthalpy of the gases is going to be rho g into u g into specific heat let us say constant pressure into the exit is T plus dT minus temperature. Because for this element at the left hand side the temperature is T it has increased in temperature over a small distance dx by dT to T plus dT and therefore, this is the value or rather, the increase in energy increase in enthalpy of the gases in energy of the gases is equal to rho g u g into c p into d t.

Where does this energy come from? The energy comes from the chemical reactions which generate so much of heat so much joules per meter square and also, I find there is some heat which is getting conducted.

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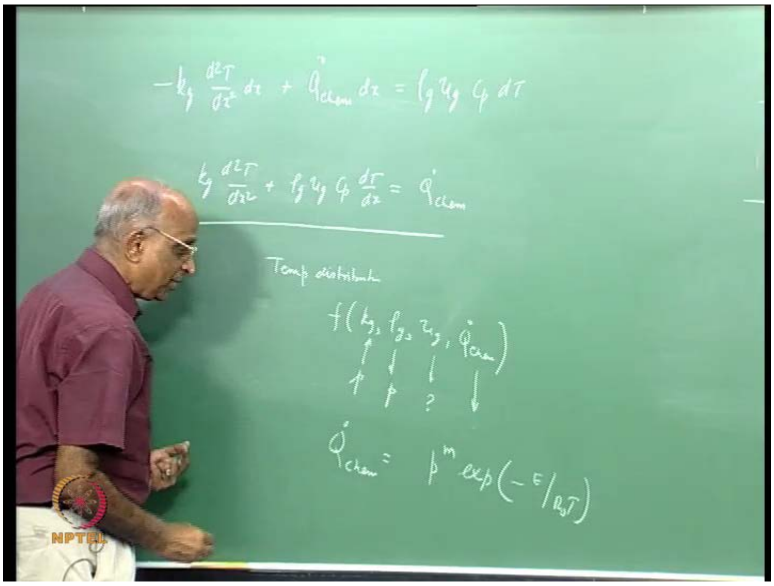

That means, this plus this must be equal to this or rather now I can put the equation down as minus k g into d two T by dx square into d x, which is the heat transfer plus I am getting some heat which is getting generated q chemical rate into d x, which is the net heat accumulation. And where is this heat going it supplies this enthalpy for this which is equal to rho g u g into c p into d T. This becomes my energy balance and we must be able to write this energy balance for any problem, we can write this equation as may be take dT I have k g into d two T by dx square. I take it on the right hand side plus I have rho g u g into c p into dT by dx is equal to dx has come out is equal to q dot chemical, where q dot chemical is the energy release per unit volume in the fizz zone so much joules per meter square.

If this is the case how do I solve this problem? See solving this problem is a little difficult in the sense all what I can solve this I can solve for temperature distribution, in the fizz zone. If I know the value of rho g u g q chemical, then only I can solve for temperature distribution and once temperature distribution is there, I can find out at the surface what is the value of dT by dx at x is equal to 0. And then find out the rate of iteration therefore, it is it is the solution will give me the temperature distribution, but this temperature distribution is going to be a function of the value of the, thermal conductivity of the gas in the fizz zone may be the density in the fizz zone may be u g in the fizz zone also, the value of q chemical.

Let us say for examine these things well the thermal conductivity of the gas should be a function of pressure of the gas. As the pressure increases may be the conductivity of the gas will go up, because I have more number of molecules there rho g is again a function of pressure u g well I have to relate it to the surface we will put a question mark. For a given u g I can solve this problem for a given q chemical I can solve this problem, but what is the rate of heat release? The rate of heat release q chemical q dot chemical in the gas depends on the pressure p to the power let us say m exponential of the activation energy minus e by r T r 0 T, where e is the activation energy of the gas I have a steric factor here.

Therefore, q chemical will be a pressure exponential minus e by r T therefore, I find well q chemical is a strong function of pressure or a functional pressure rho g is a function of pressure. The thermal conductivity is a function of pressure therefore, I can overall say well my u g whatever, I am going to get or what I wanted to solve using this particular equation should be no let us let us put it down u g is what I want p will be a function of pressure.

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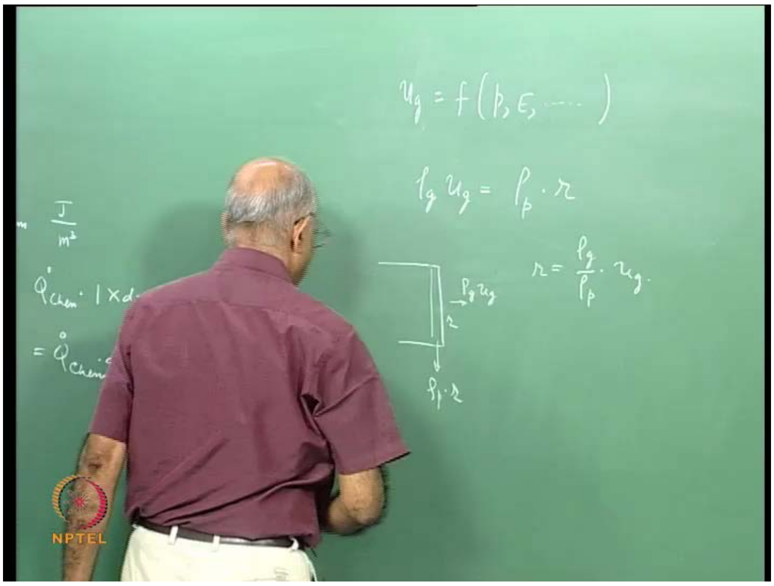

In addition I find it should be a function of activation energy and this activation energy should be a function of the composition what I have therefore; I say activation energy over here. May be a few more things may be the density may be other parameters which are there. But what I get is now I say well, the temperature distribution and the velocity of the gases which are get moving through could be a function of this and what is the value of u g? When I say I have gas in the fizz zone of density rho g the mass which is moving out this u g over here that is the velocity of gases, this must be equal to the density of propellant into the burning prolerate of the propellant.

I can hear some concentration is required all what I am saying is I have a solid, which regresses at a rate r and the gas which is that means, the rate at which the propellant is burning is r. The mass which is getting generated is equal to rho p into r, because I have unit surface area and the rate at which gas is getting generated is equal to rho g into u g per unit surface area. Therefore, this is over this is the same or rather the burn rate goes as rho g by rho p into something like u g over here.

But u g is a strong function of pressure therefore; burning rate is going to be again a strong function of pressure and the effect of the other constituents like the composition activation energy and all that. And therefore, it is possible for us to write the burning rate r in let us say meters per second as equal to a constant into pressure to the power n, where this constant c will take care of activation energy. May be the other composition and other features and pressure comes over here, and it is possible for us to write the burn rate of a propellant be the double base propellant r is equal to a which is now, I write instead of constant c a constant a pressure to the power n.

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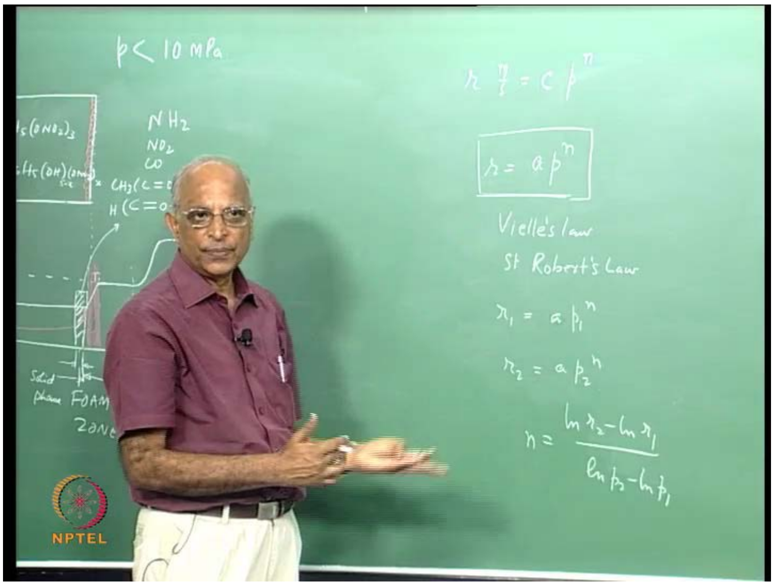

And this form of burn rate is what is known as vielle’s law or it is also, a priest in France discovered rate it is known as saint robert’s law. Therefore, what is it I have done so far? We said that the surface regression rate of a double base propellant could be written in terms of the ambient pressure p in the form r is equal to a p n, a will have the compositional features may be may be the initial temperature may be the final temperature. Because that is also going to be a strong function maybe I should have written here u g is going to be a function of the initial temperature may be the temperature T one and so on you know these are all important things.

Therefore, I put all the effects other than pressure into this a factor here that is the pre exponent and I have the burn rate law during r is equal to a p n. It becomes much easier to use a law like this rather than keep trying to solve this equation which is a little bit more difficult. And in practice we use this and how do we determine the value of n, we do an experiment we say well at pressure p 1 the burn rate r 1 is equal to a p 1 to the power n at a pressure which is little bit away I take the burn rate I measure the burn rate in a experiment. I get a p 2 to the power n and now, I use these two equations to find out the value of n which is n is equal to now I get ln r two minus ln r one divided by ln p two minus ln p 1.

Once I get the value of n I can go and determine the value of a and this is how we determine the we get the burn rate law as r is equal to a p n and how we determine the value of n and a. Just like a sparkler experiment may be at an ambient pressure, I put it in a vessel do it and do the experiment I measure the time taken to regress a particular distance measure the burn rate, then determine the value of n and a this is how we determine it, but if the pressure is higher in other words.

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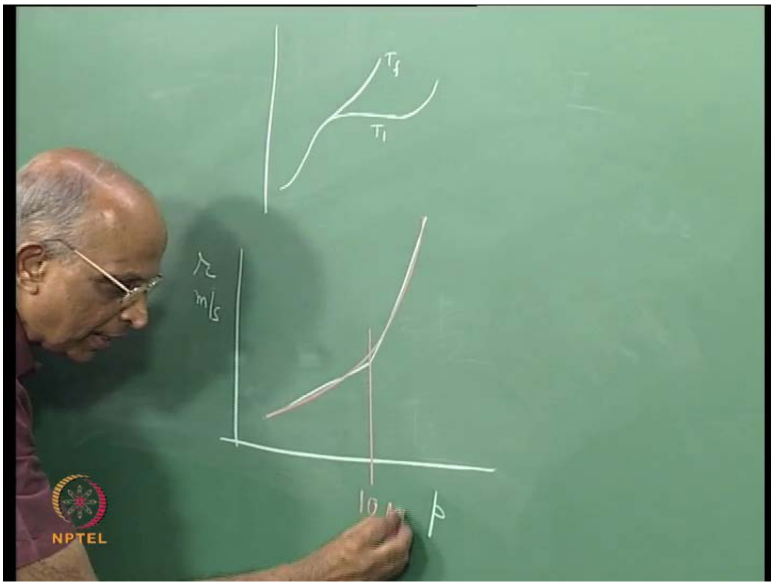

If I have the ambient pressure in excess of let us say ten M P A, then we told ourselves well there is no such thing as a intermediate T 1 zone it directly goes to something like T f over here, more heat is conducted. And therefore, if I have had to plot the burn rate r let us say meters per second, as a function of pressure at low pressures I have n which is something like this when pressure goes up it goes like this or rather, the curve will not be very mark like this may be the curve will be something like this.

This is how the burn rate varies with pressure this pressure corresponds to where the dark zone becomes absent this is something like ten M P A over here this is the plot of pressure as a function of burn rate this is how burn rate is expected to vary. But it depends you know sometimes, when you add something like let us solve to the propellant the burn rate is always not marked like this.

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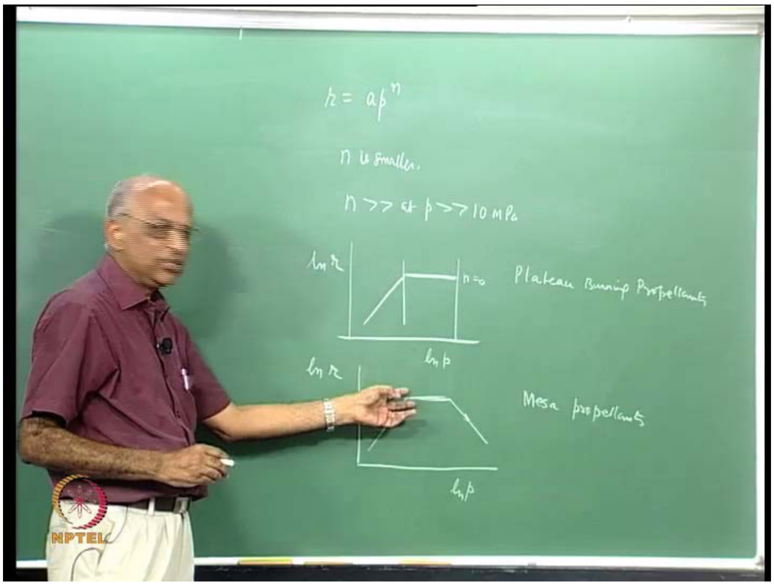

Let me again repeat this point what is it we have said, we said that the burn rate of a double base propellant can be written as r is equal to a p n, where a is a factor which considers all factors other than pressure like temperature of the gases may be T 1 may be the surface temperature, may be the activation energy and all that. And pressure is directly taken to a power n this is 1, then we tell ourselves well, at low pressure the value of n is smaller at high pressures when you have higher temperature driving the heat conduction the value of n becomes greater n is larger at when p is very much greater than ten m p a.

But we could also add some salts, some salts like lead salts, and all if I add to this particular propellant, then what happens is instead of getting a curve like this very often we get burn rate law. As a function of pressure initially picks up and there after you know it does not change with pressure that means, you have a plateau over here. In other words, I have burn rate increasing up to a pressure and it becomes a plateau such type of propellants which exhibit this feature of n is equal to 0 over a certain range of pressures are known as plateau burning propellants.

Well, some propellants have even a slightly different behavior and some may have going like this I have plateau or n is equal to 0 here, I have r versus p. In fact, I should have written ln r versus ln p over here and that is when I would have a straight line so, this should have been ln r and ln p. Sometimes the begins to fall burn rate begins to fall at higher pressures, it all depends on the chemical constituent of it and such propellants which exhibit a drop in burning rate with increase in pressure are known as mesa m e s a mesa propellants mesa burning propellants.

Therefore, what is it we did in this class today, we looked at the rate at which mass gets generated from a surface we found out that yes this surface area is important s b is important. Then we found that yes for the double base propellant I have two or three zones, I have something like a foam zone followed by a fizz zone in which temperature increases to some intermediate T one, then I have a dark zone in which the temperature is more or less constant followed by a zone in which temperature further increases.

We looked at the events happening at the at the fizz zone and not in the foam zone mind you in the foam zone it is getting conducted and comes over here. We wrote an equation and we were able to say that the velocity of the gases in this zone are dependent on pressure and the initial temperature may be the T I T 1 may be the surface temperature activation energy and all that. And since the velocity of gases is directly proportional to the burn rate r of the propellant, we said that the law is r is equal to a p n which is known as Saint Robert’s law or vielle law.

There after we told that since for when you have the reactions happening directly at high pressures; that means, instead of having a dark zone you do not have that. That means, at high pressure temperature increases from surface temperature directly to the flame temperature more heat gets conducted therefore, n is higher therefore; you have this procedure like you have small n followed by a large n for the double base propellants. Then we said well, if I add some salts I could have something like a plateau burning propellant or a mesa burning propellant.

In the next class, we will take a look at composite propellants, and then put the whole thing of burning rate. And see what are the choices we should have, how should r is equal to a p n, are there some scriptures anywhere on n on how do we ahead matching the propellant burn rate with the design of a solid propellant rocket. This is what I will do in the next class. Thank you.