Rocket Propulsion

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Lecture 25

Review of Solid Propellant Rockets

We will finish our discussions on the solid propellant rockets today. Let us start with something amusing.

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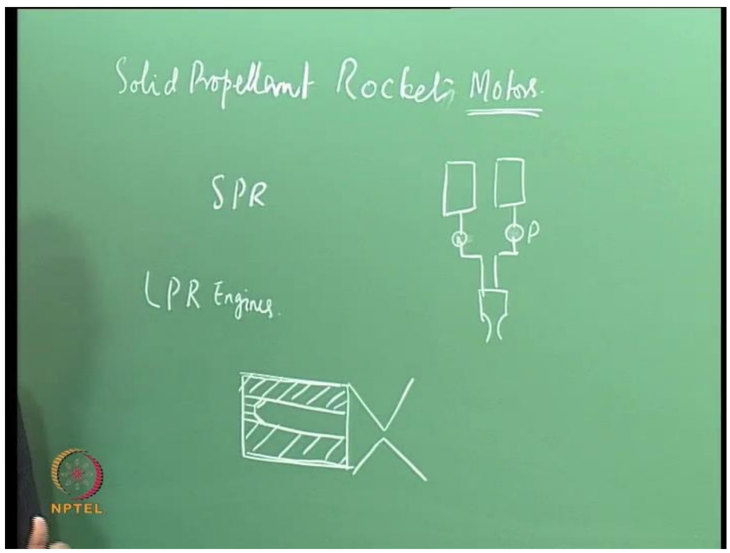

Solid propellants rocket, abbreviated as SPR are known as solid propellant rocket motors. Whereas, when we talk of liquid propellant rockets, liquid propellant rockets are known as liquid propellant rocket engines. What do you think is the reason calling one as motor and the other as engine? You know in many textbooks you find this solid propellant rocket referred to as a motor whereas, liquid propellant rocket referred to as an engine. What do you think would be the reason?

Let us go back and look at the construction of a solid propellant rocket. We have a case in which we put some insulation. We will revise it again towards the end of the class. Then I have a nozzle. The propellant grain, which could be a radial burning grain could be a star or something else is contained within the case.

And what else we did. An igniter is placed in the port volume of the grain. It generates a hot plume and ignites the propellant grain. If we talk in terms of a liquid propellant rocket engine, we should have tanks, which carry the liquid, we have the propellant lines to the chamber. And to be able to pump the liquid propellants, let us say the liquid fuel we need a pump, we similarly need a pump here for the oxidizer. Therefore, we have moving parts such as pumps, which moves whereas to drive the pump we need again a turbine. we have moving parts in a liquid propellant rocket. Whereas, a solid propellant rocket has no moving parts; it is just simple case enclosing the propellant and igniter. Therefore, for some reason or the other a solid propellant rocket, because it has no moving part is referred to as a motor. In fact, the case is referred to as a motor case. A liquid propellant rocket considering that it has moving parts is referred to as engine.

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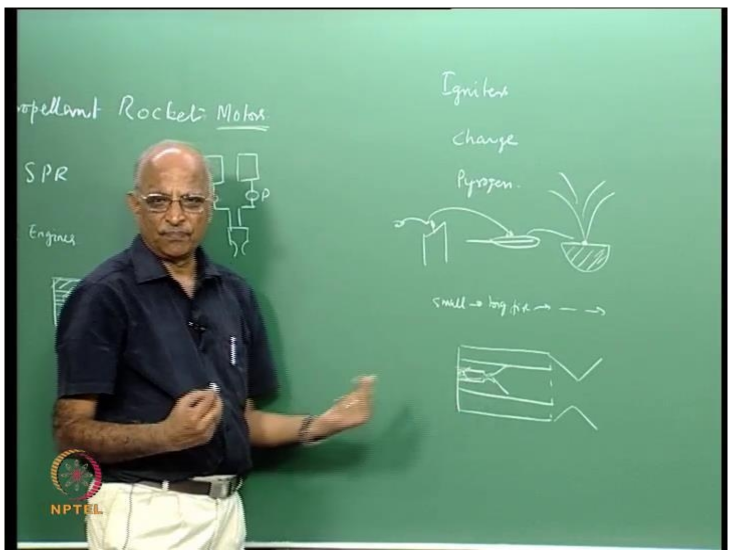

Now with this introduction let us see where we were in the last class. We discussed the igniters. And let me just briefly go through what we covered in igniters again. See before discussing igniters we were very clear how to be able to define the burning surface area; the configuration of the grain according to the amount of thrust which is required. We could design the grain. The igniter jet, impinges on the propellant surface, pressurizes the cavity and then ignition takes place. We had different types of igniters: one was a pyrotechnic igniter in which we have a charge which is easily ignitable whereas we also talked in terms of a pyrogen igniter wherein we put a small rocket motor itself as the igniter in a larger rocket.

What is the principle? Let us just say whenever we make a fire - like for instance I want to light a candle let us say. I use a matchstick and light this candle. I cannot use this matchstick if I were to light a sparkler. I do not generally use a matchstick, because it requires more sustained flame to ignite it. And therefore, I use a candle for lighting this sparkler. Now again I say I have something like a Bengal pot, it is something like a mud pot in which I put some pyrotechnic composition. I cover it over here it is something like this, I light it over here and we produce a plume of sparkles. This is known as a Bengal pot, because this type of fire cracker originated in India in Bengal and therefore, to light it, I use a sparkler. I show the sparkler here and light this. What is it we see? A small fire is required to make a little bigger fire. And a bigger fire is required to initiate an yet bigger fire? And with this bigger fire we can make a still bigger fire.

That means, in practice to be able to ignite anything a small fire is required to make a bigger fire and so on. A bigger fire is required to ignite a still bigger fire; and that is how things are if we have a furnace we do not put an electrostatic spark to ignite the fuel air mixture in it. We create a pilot flame with the pilot flame we ignite it and so on. And so also in solid propellant rockets what we do is we use a small rocket motor over here. And that small rocket motor has a nozzle; let us say this is the case over here, we put a small rocket over here. That means, we have something like a nozzle over here, we have another igniter for it, and this will contain a squib for its igniter. It is similar to a small fire makes a bigger fire, maybe makes a still bigger fire and so on. The pyrogen igniter and makes a bigger fire which ignites the rocket.

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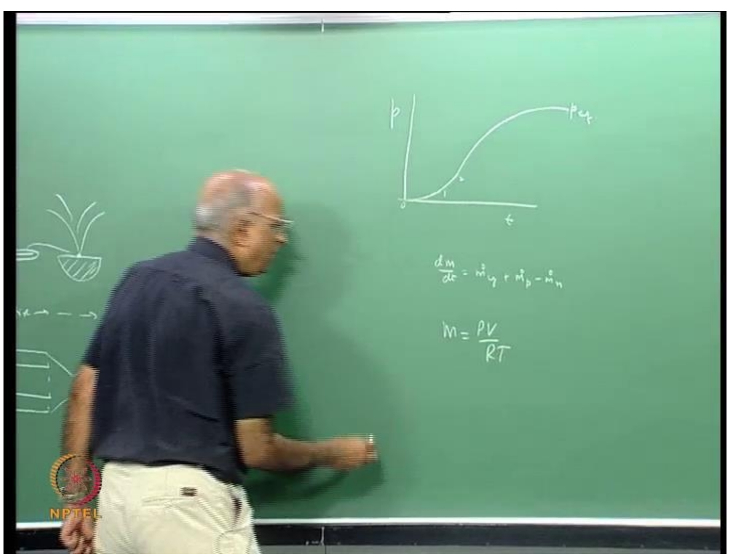

Therefore a pyrogen is a small rocket, which ignites the main rocket. And what did we note? If we have a large rocket and if we look at the pressure time trace, we have something like it initially ignites over a small surface locally. What the igniter does is it pressurizes the chamber to some small value. And also transfers heat over here and therefore, we have local ignition from let us say 0 to 1. And then the flame spreads over the surface to 2 and after the flame has spread it reaches the equilibrium pressure which we say is p equilibrium.

We derived expressions and we found that the transients could be easily be predicted. How did we predict the pressures? We had dm/dt that is the rate of mass accumulated or developed in this cavity. The rate of change of mass is equal to the rate at which the igniter supplies the mass at that particular time plus the contribution, which comes from the burning of the propellant and the spread of the propellant minus the rate at which the flow takes place through the nozzle. And we were able to say m is equal to PV/RT. And we took the simple case where in dm/dt corresponds to the condition when the surface entire surface of the propellant has just got ignited that is local ignition of a small surface followed by the entire surface getting ignited and we were able to get the equation to this curve and what was the equation?

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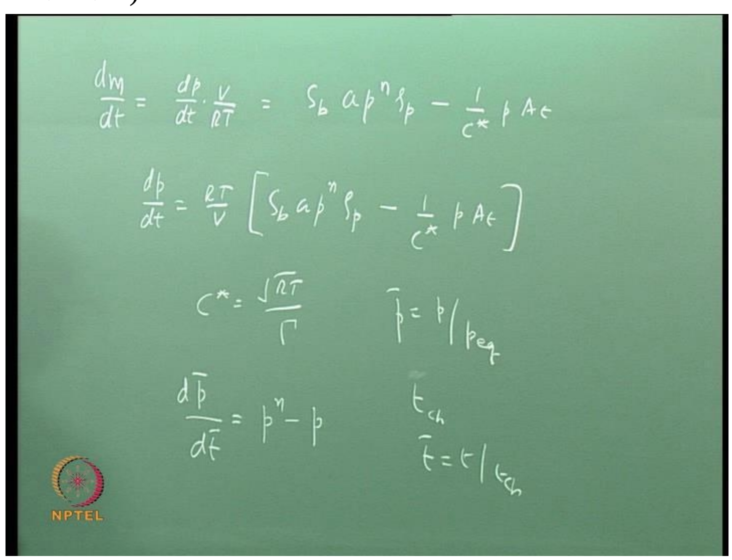

We wrote an expression for dm/dt. And you see how simple it is; m is equal to PV/RT that is dp/dt × volume (volume is constant) V/RT = the entire surface is burning Sb × r viz., ‘a’ × p^n × ρ_p i.e., the rate at which mass is getting generated – 1/C* × p × At. Therefore when we solve this equation, we had this within the bracket, Sb, ‘a’, p to the power n density of the propellant minus $1/C^* \times p \times At$. And what else did we do? We said C^* was equal to $\sqrt{RT}/\Gamma$, where $\Gamma = \sqrt{\gamma}\ (2/(\gamma+1)^{(\gamma-1)?2(\gamma+1)}$.

We replaced RT by Γ^2/C^{*2} in terms of capital gamma squared into C star squared and we were equation we were able to get the equation in a non-dimensional form. How did we get p bar? We said p bar is equal to pressure at any point in time p divided by equilibrium pressure and this was the final steady state value at burnout. And we defined a characteristic length which came from $V/At = L^*$. L^*/C^* we said has a unit of time; we called it as characteristic time. And we said we will take a look at it when we study combustion instability. We also said that the non-dimensional time t bar is equal to t by t characteristic. And therefore, we were able to get say t characteristic here by t bar. We got dp bar by dt bar is equal to p bar to power n – p bar.

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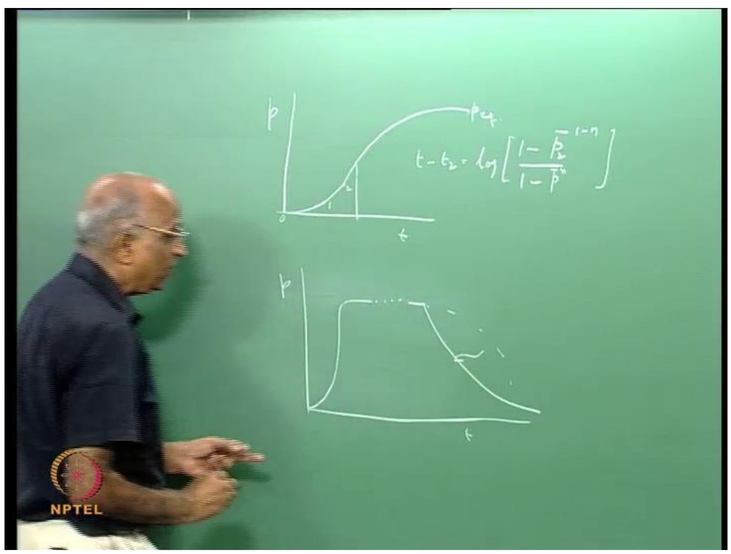

We integrated this expression and got it in the ln form; that means pressure at any point or the time after event 2 between let us say between 2 to 3 was derived as logarithm of 1 minus p at 2 non dimensionlized to the power 1 minus n, to the power 1 minus p at anytime to the power 1 minus n is the expression for the time. Or rather we found it droops after some particular time. We followed the same logic to be able to find out what will be the variation of pressure after the propellant burns out in a rocket. Let us say p over here, t over here on the X axis; and we said the motor ignites, keeps on burning till all the propellant gets burnt. What will be the signature for the pressure transient after the propellant gets burnt? What will be the equation to describe this event? Does the pressure go like this or does it go exponentially like this; we were interested in the shape. And the equation we got for this was quite similar for the ignition events. All the propellant is getting consumed over here. Therefore, the equation for that particular case of depletion that we derived in the last class was dp by dt was again equal to RT by V into the rate of mass depletion by nozzle which is minus p × At / C* i.e., m°n.

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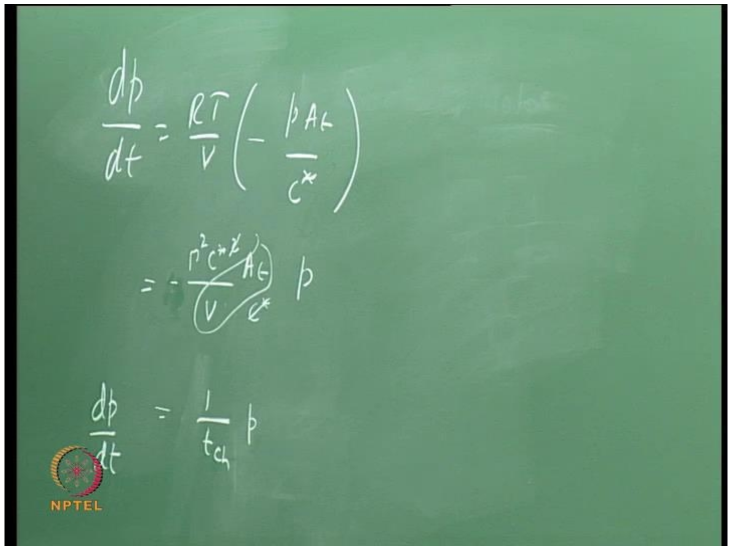

And we followed the same non-dimensional procedure. RT is equal to capital gamma squared × C^{*2}. And therefore we got gamma squared into C star squared divided by V, we took At outside, and the value of C* and p and this negative sign of mass leving the rocket. And with V/At = L* i.e., volume by throat area, which is the characteristic length at burn out of the propellant grain. And we had C* over whose unit is velocity and with V/At = L*, we could also write this particular equation in the form as 1 over L* ÷ C* which is equal to the characteristic time with a negative sign; i.e., 1 over characteristic time, because length over velocity has a unit of time. And therefore for dp/dt = p divided by the characteristic time.

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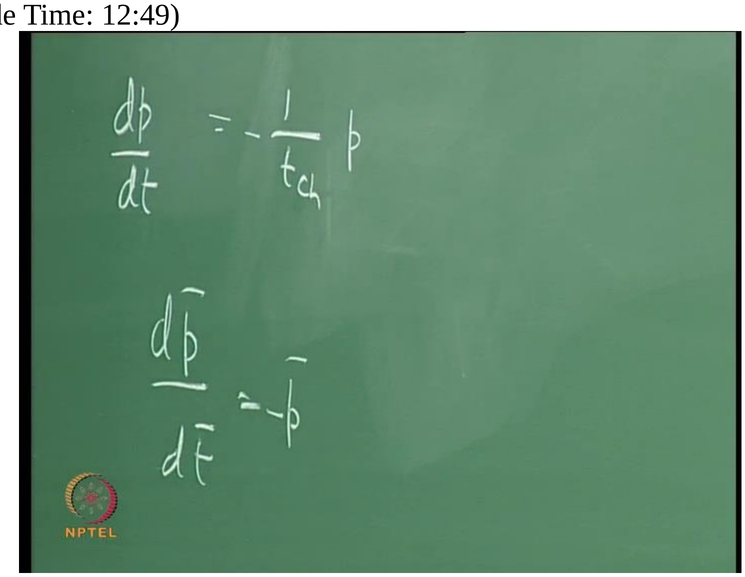

We can write this equation as dp bar by dividing both the sides by equilibrium pressure. By bringing the characteristic time tch to the left side, we get dt bar that is non dimensional time. This is equal to p bar. Or rather this equation expresses the differential of non-dimensional pressure with respect to non-dimensional time. Mind you there is a minus sign.

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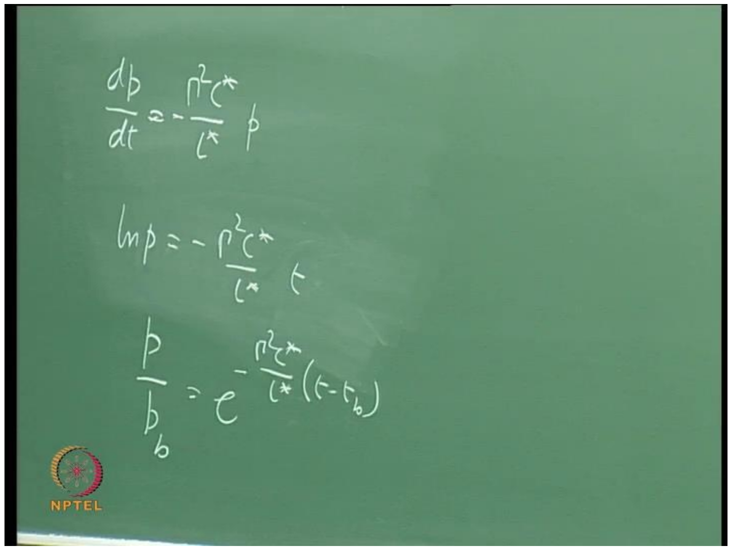

And this tells me that dt is equal to − dp/p. Rather the time taken after the burning of the propellant is completed, tb is when burning gets completed; we have t − tb. Therefore, we get t − tb is equal to natural logarithm of the pressure by pressure at burn out. The decay is of pressure would be exponential and to reach zero value, it is going to take a very longtime. And we did it dimensionally the other day. We would have got Γ^2 C^* /L*. We must be able to do this in different ways. We could have got dp/dt $= -\Gamma^2$ C*/L*. And if we were to integrate, we get ln p = − Γ^2C*/L*(t-tb). That means, the pressure continuously decays with time.

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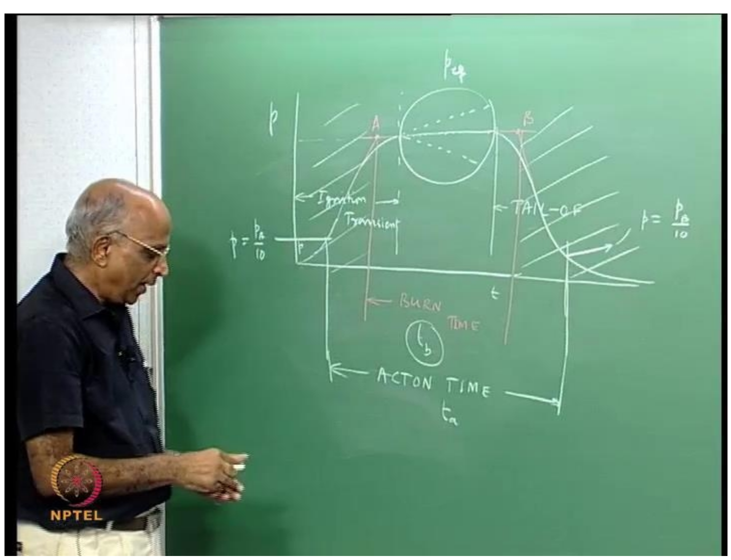

Why are we repeating this? See there must be some reason. The reason is whenever a rocket motor ignites, the pressure changes with time, starts slowly building up as flame spread progresses, then reaches after chamber filling interval the neutral, progressive, or regressive equilibrium value. This particular zone is equilibrium pressure; that means a steady state pressure. At the end of this what happens is well all the propellant gets consumed and the chamber pressure and thrust decays out. We have the transient for ignition; the ignition transient followed by a period of steady or equilibrium burning which will be much longer, and then the time when it burns out or you have we called it as tail off. How do we use this signature of the transients and equilibrium burning to define the effective burning times? It becomes a little complicated or subjective and there are standard procedures to do it.

Let us consider the case of neutral burning. We plot a tangent to this particular pressure time trace in the zone of neutral equilibrium burning. So also we plot a tangent to the curve in the ignition transient zone. We get a particular point of intersection of the lines here. Similarly, we plot a tangent here in the tail off curve and the point of intersection of the tangent of the tail off curve and the equilibrium burning curve is obtained. We call these points as ‘a’ and ‘b’ respectively. And we now see, burning is taking place during the end of the ignition transient and the initial phase of the tail off and the precise points of the start and stop could not be found. After the intersection of the tangents, we get the points a and b as the start of burning and end of burning and the time from a to b is called the burn time. And it is denoted by the symbol tb. And this is how we characterize a solid propellant rocket motor for the burn time of the propellant. This means that the burn time of this motor is so many seconds or so many minutes or so.

But we also realize during the period before start of the burn time, the rocket motor is still giving us impulse or some momentum. It is contributing to impulse even earlier and after the burn time. Therefore, when we want to define a mission and for a mission a certain impulse is required. We therefore take the maximum pressure value at the point of the intersection of the tangent line to the ignition transient and the equilibrium pressure curves. This pressure is denoted by pa. We divide it by 1 by 10 that is 10 percent of the value. Similarly, I get the value of maximum pressure at burnout pb. We take 1 by 10th of this value. That means, the pressure corresponding to this decaying pressure point is equal to pressure corresponding to the b divided by 10. And now here also we get the certain impulse here. The impulse may be small.

The particular time between 10% of the maximum pressure at the start and at the end is called as the time of action of the motor or action time. We denote it by ta. In other words, when we have to plan a mission, we get thrust over the action time. However, to characterize the motor in a test or otherwise, we are interested in the burn time. And we see that the action time is greater than the burn time.

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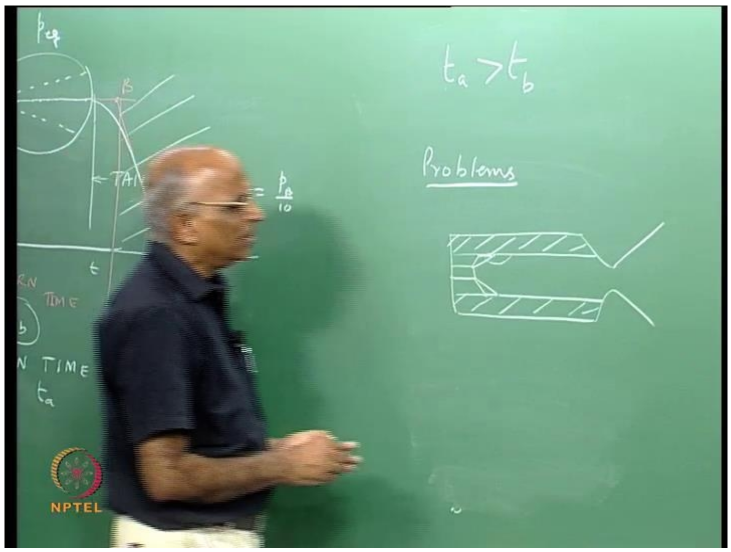

Now let us examine one or two small problems we can have in solid propellant rockets. Why we are considering this is whenever we make a rocket; let us say we have a rocket as sketched here. Let us say it has a radial burning grain. We add an igniter to it. And we told ourselves the other day most of the igniters are pyrogen igniters, because normally the rocket motors are quite large.

We were quite clear how to go about making an igniter. The igniter must pressurize this cavity to some value, not very high value, such that a flame can be near the surface. The igniter must also give some energy to the propellant surface and we said propellant requires some minimum energy for ignition. We have plumes from the igniter and it ignites a particular surface. These were all the requirements and thereafter the flame spread and pressurization take over. We had this particular transient curve for local ignition flame spread and the pressurization of the cavity; But sometimes when we do a test or an experiment we had the pressure going up instead of following the ignition transient curve shown earlier.

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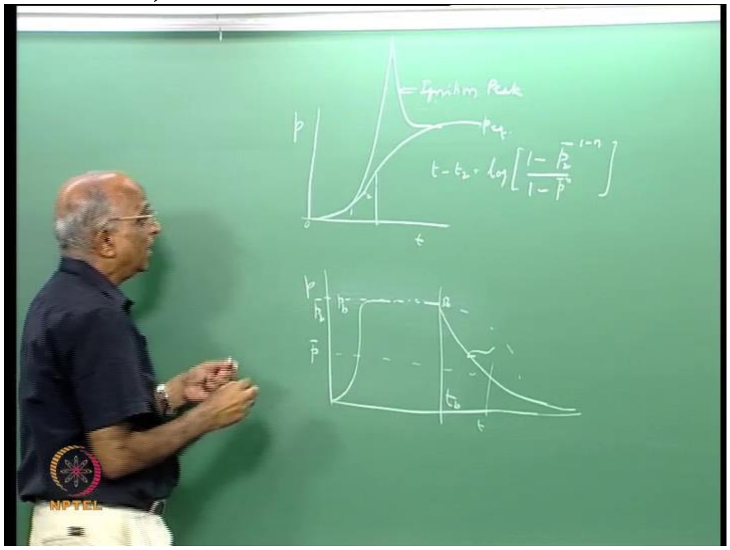

Very often the pressure goes like this in the form of a spike and comes down after spiking to the equilibrium pressure. In other words we get a peak of pressure much greater than the equilibrium value. That means, we get something like an ignition peak in the process of ignition transient. The pressure peak can burst the case or provide an unplanned thrust and acceleration and this is detrimental. Why should such an event take place?

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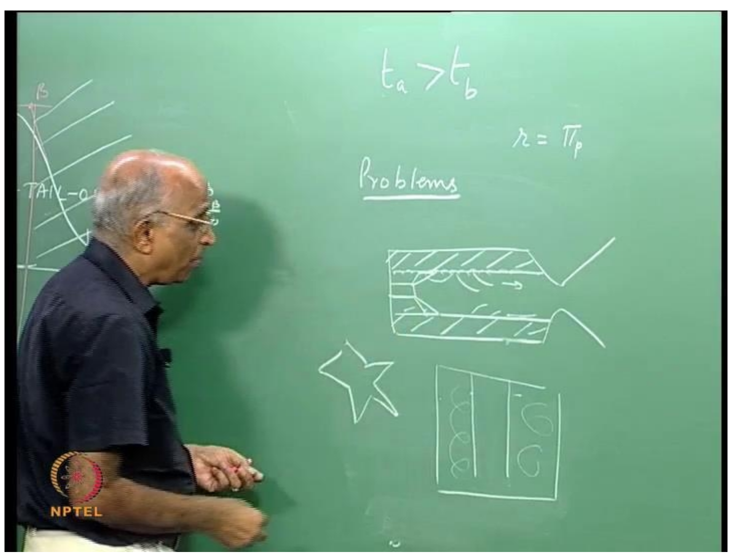
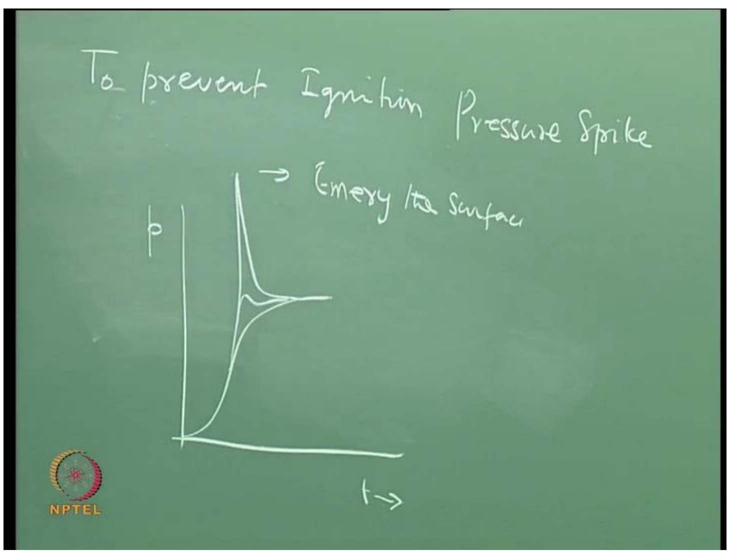


Let's take a look and address the parameters. How do we make a propellant grain? We take a case motor case. Inside it we put a mandrel; if we want to make a cylindrical grain we put a cylindrical rod, pour the propellant slurry between it and the case. If we want to make a star grain well the shape of this mandrel would be star shaped. The slurry is then cured and we remove this mandrel. We have this particular shape of the grain. And some times to remove the grain is difficult and therefore we use some agents which a like silicon oil which are essentially insulators to be able to easily remove the mandrel from the grain.

Now if the surface of the grain so formed is such that it is not easily ignitable. What happens is that we are transferring energy the grain; it gets heated and as it continues to get heated its temperature increases. When it begins to burn it starts burning at a higher temperature, and since it starts burning at a higher temperature the value of the burn rate is now influenced by the temperature sensitivity factor. And therefore the burn rate is higher since burning takes place at a high temperature. It produces much higher rate of mass or it burns with a higher speed. And therefore, you have a higher amount of mass and energy, which is getting released and therefore, the pressure could go up. This is one of the reasons for the spike in pressure. The second reason could be, we have higher velocities especially towards the nozzle end of the grain surface which if high enough can enhance the burn rates. (Refer Slide Time: 24:19)



But, to be able to prevent the pressure spike what this normally done is we take something like an emery paper and remove the surface defects and ensure that the surface of the propellant is easily ignitable. Let us put down the points to prevent ignition spike ignition in a solid propellant rocket. What we do is we emery a surface. Take an emery paper may be make the surface make sure oxidizer and fuel are readily available, and it catches fire easily. You have to make sure, that the surface is such that some other reason like burning due to increased velocities, which we call as erosive burning are not possible. We will consider shortly about erosive burning.

We can always tolerate a small value of the spike; but must guard against it. Something that we missed out was that we often require to ignite a motor under low ambient pressures or in vacuum of space.

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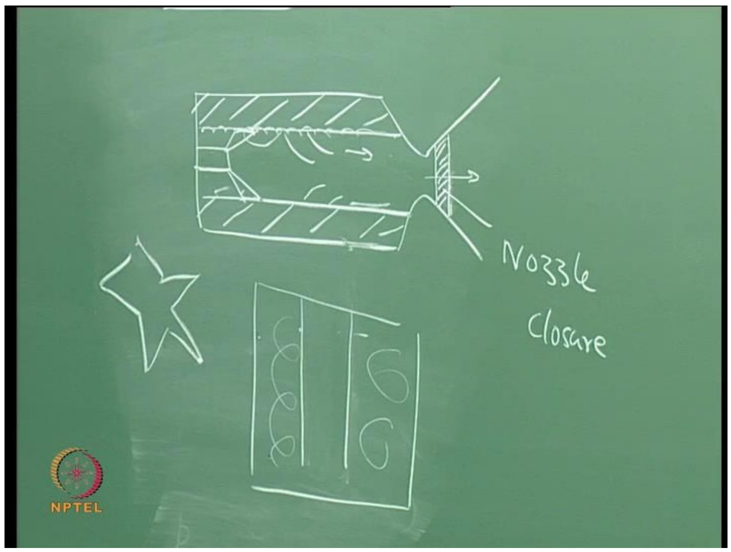

Since we need to build pressure in the port volume, we put something like a closure at the nozzle. When pressure builds up and the motor is ignited, the closure is thrown out. We make sure that after adequate pressure is generated around 5 bar to 6 bar, the closure is dislodged. This closure is known as a nozzle closure.

This is all about solid propellant rockets. We have considered the propellant burn rates, we have considered how to go about making grains of different configurations to get thrust. And then we looked at igniter; we looked at the action time and the burn time. And therefore, maybe we should put things together at this point in time before we close our discussions on the solid propellant rockets.

Let us start with propellant burn rate r. How did we define the burn rate or how did we determine the burn rate. We said that we make a propellant strand may be something like a cm in diameter. We could put it in a chamber and pressurize the chamber to whatever pressure we are interested in. Then we ignite the surface and measure the burn rate when the burn propagates through a particular distance. We control the pressure in this chamber. This particular chamber in which such strands are burnt is known as Crawford bomb. It is something like a bomb type of a calorimeter in which we burn the propellant, but all what we do is we put a series of fuse wires at known distance apart along the line of burning. An electronic timer is used to find the time taken to burn between the individual segments of the strand. The distance L divided by the time is the burn rate r at the particular chamber pressure.

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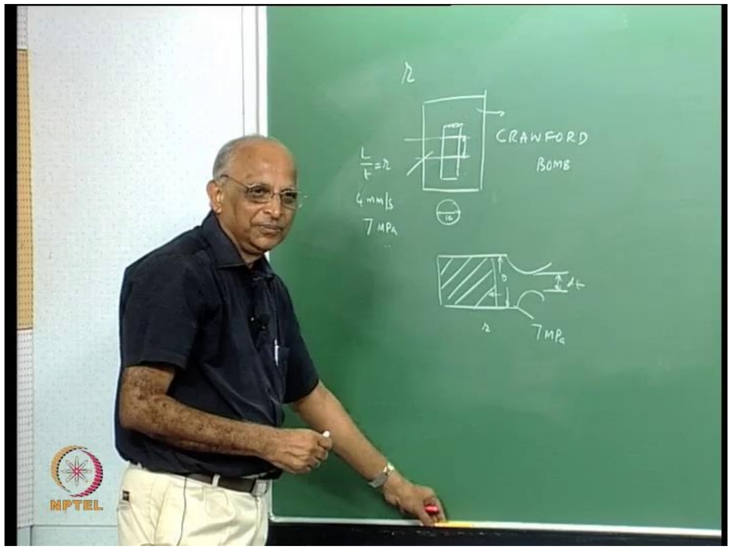

Can we use this burn rate in a rocket motor? Let us say the same end burning configuration of propellant grain is used in the rocket motor. What we have is the diameter of the grain is D and the throat diameter is d_t. We want to find out the burn rate of the grain the rocket chamber. We measure over here it gives me let us say 4 millimeters per second at a pressure of let us say 5 or let us say standard pressure 7 MPa. The question is will we get the same value of r as in the Crawford bomb or should we get a different value. What is your take on this? Should it be the same as measured in a strand at the same pressure? How would you look at this problem? We again go back and write the simple equation, that we derived for burn rate.

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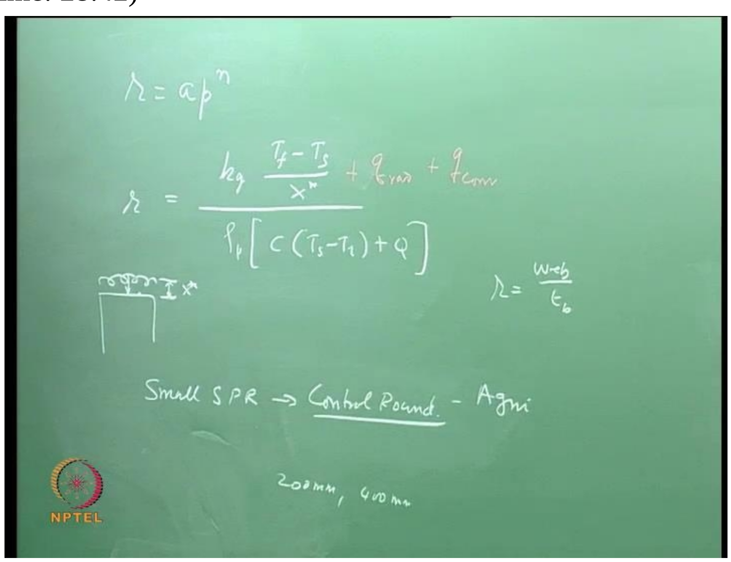

We got the equation r is equal to ap^n. How did we get this equation? We have the surface and the flame standing off at a distance X* from the surface. And how did we get the burn rate r. It is equal to the heat which is given over here, thermal conductivity of the gas above the surface, into the temperature of the flame minus temperature at the surface, divided by X* is the heat which is conducted divided by ρ_p into specific heat into surface temperature minus the initial temperature plus the exothermic heat release at the surface; we derived this based on the simple model.

Now can we look at this, for the experiment in the rocket and the experiment in the strand burner? And would it be different in the two cases or should it be the same? This is a perennial problem we have with solid propellant rockets. Now what is happening in the Crawford bomb is that the ambient is all cold gas even though it is at the same pressure. Here the ambient is hot gas therefore, we will have heat radiation coming on the surface. In other words when we test a motor we will have something like q radiation coming on the propellant surface. We could also have in a radial burning grain q due to convection coming on the surface in addition to the radiation.

And therefore, the burn rate in a motor should be higher than in when it is tested in a strand burner. And therefore, to determine the burn rate what is done is you have to test it in a small solid propellant rocket and these propellant grains are known as control blocks or control rounds, because I cannot really use this standard Crawford apparatus to determine the burn rate. I have to use a rocket configuration, because it is more representative of the actual. May be when I am developing different propellant formulations, we can screen them in a strand burner. But the final burn rate is always derived with a small solid propellant rocket itself. Which is known as a control round; in India we call control round as a Agni round, but let us not confuse it with Agni missile.

The small rockets used for burn rate measurements may be of diameter around 200 mm and length around 400 mm with cylindrical burning. Burn rate is equal to web thickness divided by the web burn time. And that is how we determine the burn rates in practice. The problem now gets more confusing for the following reasons. Let us consider two cases of solid rocket motors having the same composition of the propellant grain. The solid propellant rocket used in space shuttle is a very large with diameter is around 3.8 meters diameter the length is around 40 meters.

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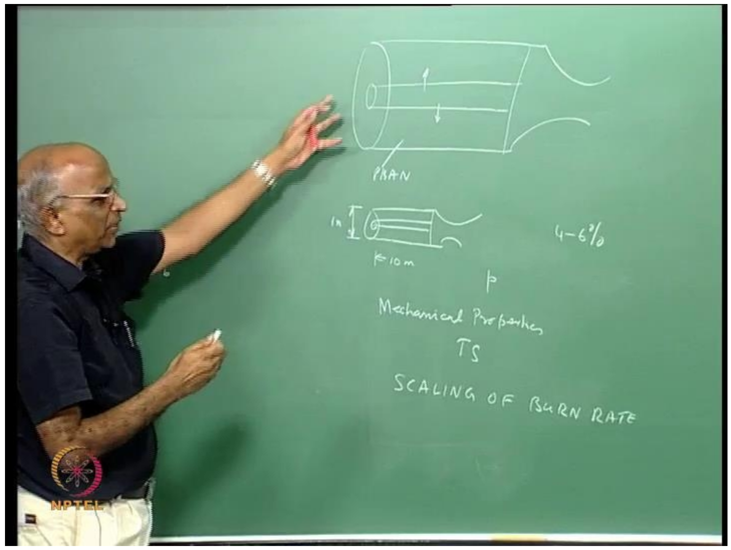

It has a star shape grain, but we assume a simple radial burning. Let us say that I have another motor of smaller dimensions using the same PBAN propellant as the solid rocket booster. Let us say that this small rocket has a length of 10 meters long and diameter of 1 meter. If the pressures in both are the same, will the burn rate determined at the same pressure be the same or different. Again we look at the radiation heat transfer; it depends on the mean beam length of radiation. Therefore, I expect the burn rate in a larger motor to be different, but it is not necessarily true; there are other factors like mechanical properties of the propellant. Why I say mechanical properties mechanical properties could be hardness could be tensile strength, could be the ductility of the propellant. And during burning I could have some deformation taking place all those things are going to influence the web thickness.

And therefore, scaling of burning rate with size of the motor or size of the rocket is always of interest and a problem of interest. We observe as we go from a medium size motor to larger size, the increase in burn rate increases by something like 4 to 6 percent generally. And after particular size, it is not significantly influenced by the size. But we have to verify it through models. And what are the models we use; we go back to our basics, write the equation find out what is the role of convection and radiation and solve the problem.

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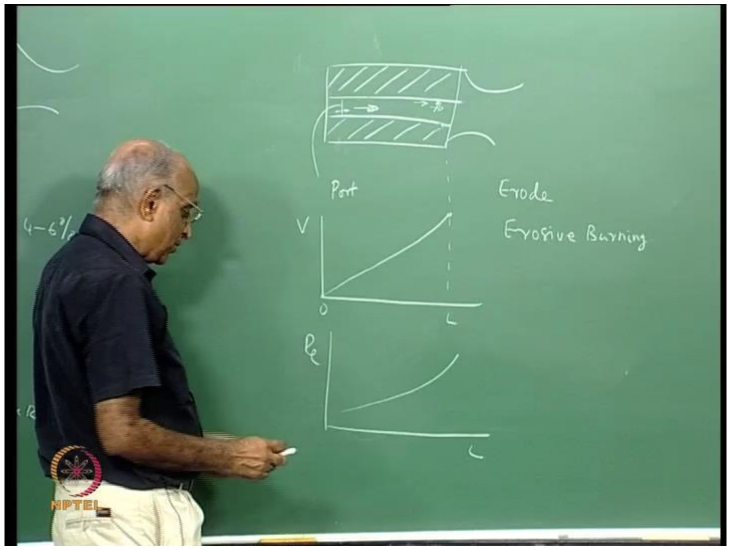

This brings me to the last point, namely if we were to have something like a long propellant grain. Like let us say we have a internal burning grain, let us say radial and the initial cavity or port diameter which is also defined as port of a rocket grain is of small diameter. And as it burns at the surface let us say this is the propellant grain, gas is coming out let us plot the value of velocity of the gases which is moving as a function of length starting from the head end towards the nozzle end.

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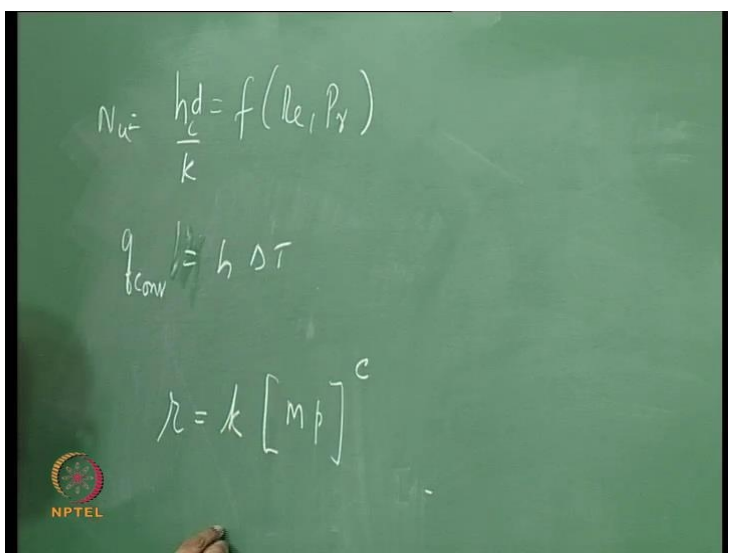

At the head end there is hardly any velocity, but as more and more gas is generated, the velocity is increasing towards the nozzle end. Velocity is a maximum at the nozzle end. Now what does velocity does to a surface which is burning. Well it can erode the surface like in a river. Let us say a river is flowing and what does current of velocity do? It drags the sand from the river. So, also I could have something like erosion. Let us write it down. The velocity could erode the propellant surface; in other words I could have something like an erosive burning. Mind you propellant was heterogeneous; composite, it is sort of eroding the surface or erosive burning, but more than erosive burning we find velocity here is higher therefore, the Nusselt number or the Reynolds number will be greater. We have Reynolds number as a function of length and it increases with velocity. If Reynolds number increases, well the Nusselt number or heat transfer coefficient is bound to go up.

Therefore we are also going to get increased convective heat transfer. In other words we can talk in terms of erosive burning arising from convective heat transfer, and when we do such a modeling and calculate the new value of heat transfer coefficient by convection, it is equal to function of Reynolds number into Prandtl number. And this we write in terms of Nusselt number as hd by k. And therefore, we can always find out the Nusselt number and once we know heat transfer coefficient, we can find out what is that q convection and find out the increase in heat transfer rate. When we do this we find that the burning rate can be expressed in terms of a constant into something like a Mach number into the pressure to the power c (r $\approx M^c$_.

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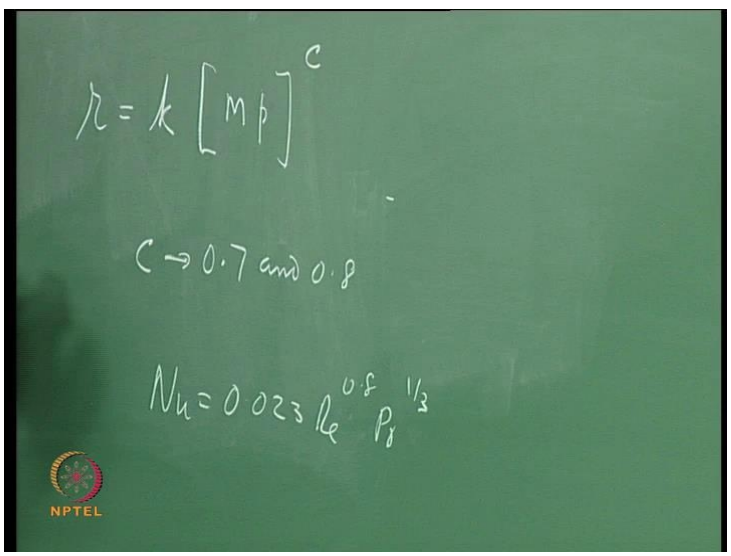

The value of the exponent c is typically between 0.7 and 0.8, which is something like in the standard correlation for Nusselt number. It is equal to 0.023 into Reynolds number to the power 0.8 into Prandtl number to the power 1 by 3 for turbulent flow. This suggests that convective heat transfer does play a role. In addition to pressure we have Mach number effects and this is what gives us the erosive burning.

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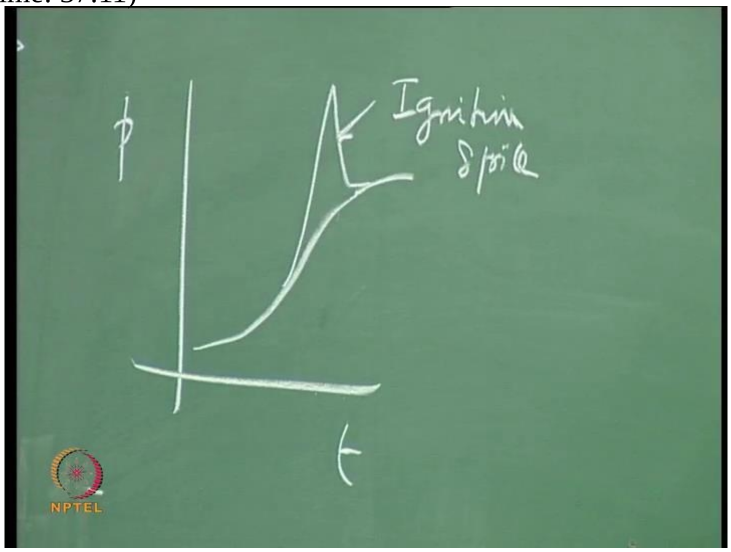

And this erosion effect, because it increases the burn rate can also lead to the ignition spike since at this time the port volume is small and velocities would be large. The larger mass burning rates could provide the spike.

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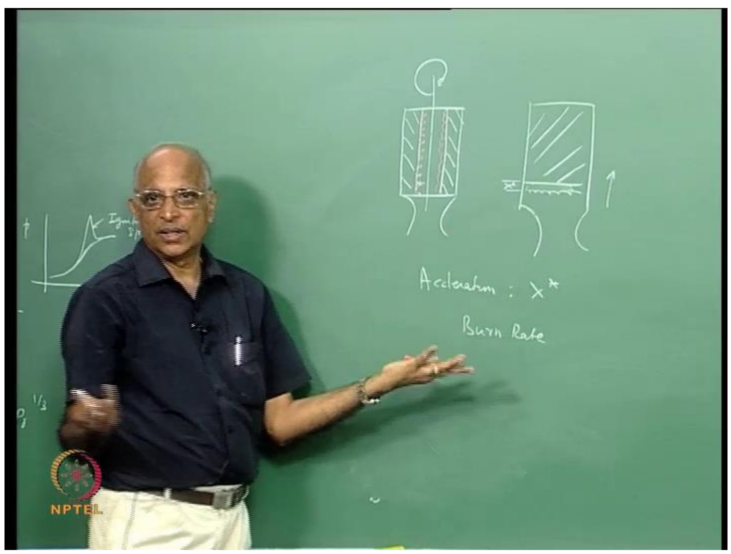

Supposing let us say we are launching a particular solid propellant rocket. And to be able to stabilize it sometimes is spun i.e., it rotates on its axis. We have let us say an end burning grain, something like this it is burning over here, it is being launched like this. We also have a spinning of a radial burning grain. And why do you spin to make it stable like just like we have a top which when it spins is stable.

Now what is happening is the burning surface area. In the frame of reference of the burning surface, we have aluminum, which is burning over here; it gets pushed towards the surface. Therefore, I get the effect of local acceleration and the effect of acceleration is to be able to push it towards the surface. And therefore, we can say that acceleration will affect the X* viz., the flame standoff and therefore, it will also affect the burn rate. We can thus find the effect of acceleration due to the spinning. All we have to find out is how the acceleration influences the stand of distance of the flame. If we can find it out through a simple model, we can find out the influence on burn rate. We know the centrifugal force from the acceleration. We know the mass of aluminum particles, which are burning and therefore we can do this problem. Let us quickly revise through and then address one or two of the very major issues which was faced in solid propellant rockets namely the control of thrust. Let us quickly revise in two or three slides what we have been talking of.

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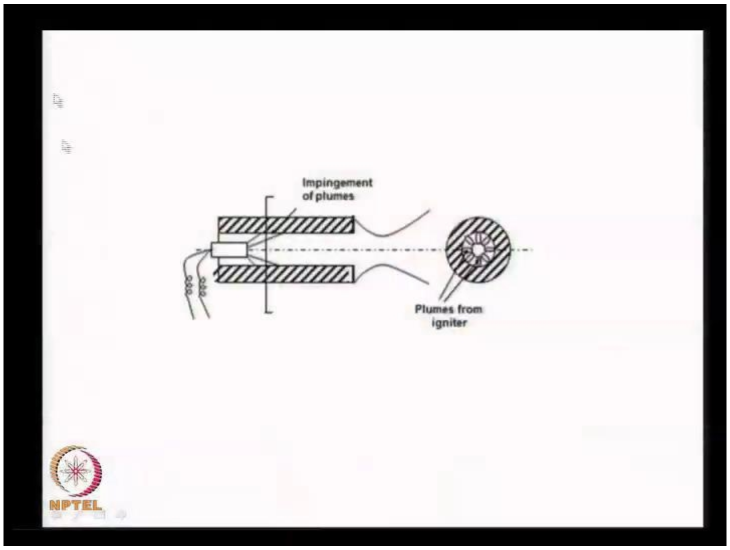

This is an igniter may be a pyrotechnic igniter. It produces these plumes which impinges on the propellant surface, ignites the surface also pressurizes the cavity. These are the individual plumes, which are igniting the surface. The flame spreads and then the gases move out through the nozzle and this is how ignition takes place.

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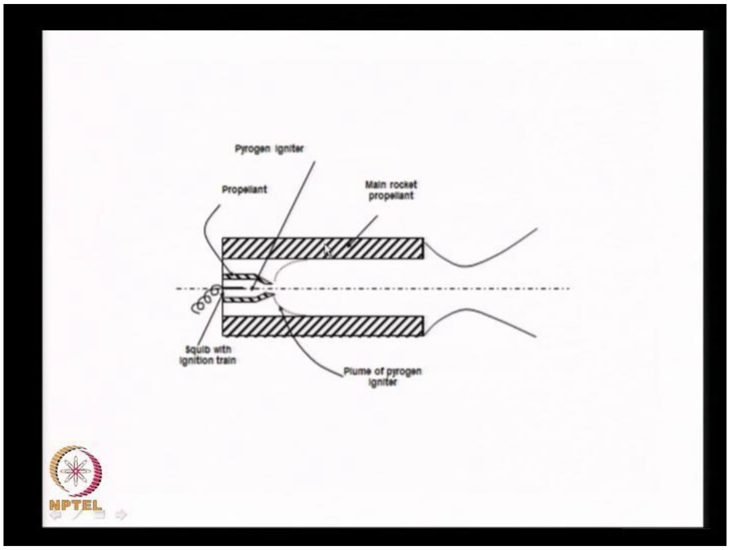

Let us go to the next one. This is a pyrogen igniter, a small solid propellant rocket. This has a pyrotechnic igniter here, squib over here burns here, ignites this surface and flame moves forward. That means a pyrogen igniter is a small solid propellant rocket.

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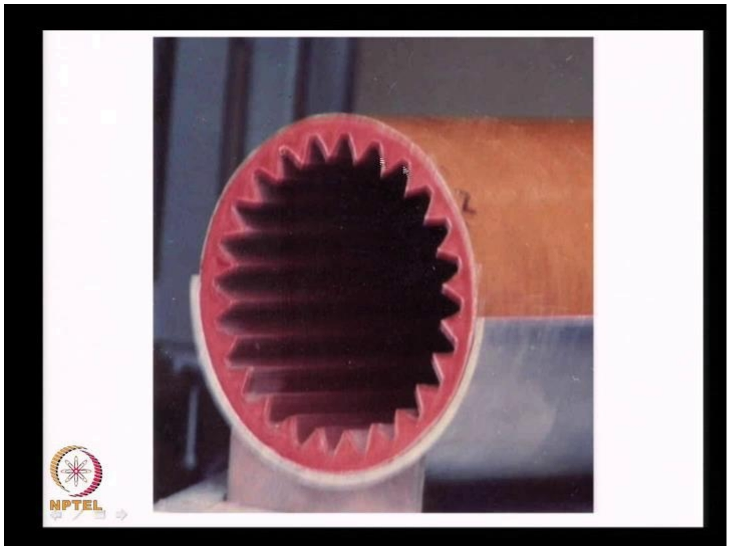

See this is how pyrogen propellant grain looks. It is like a solid propellant rocket only you do not need to generate thrust. We provide a multi point star shown in red. When the propellant here is ignited, it generates hot gases that ignite the main motor.

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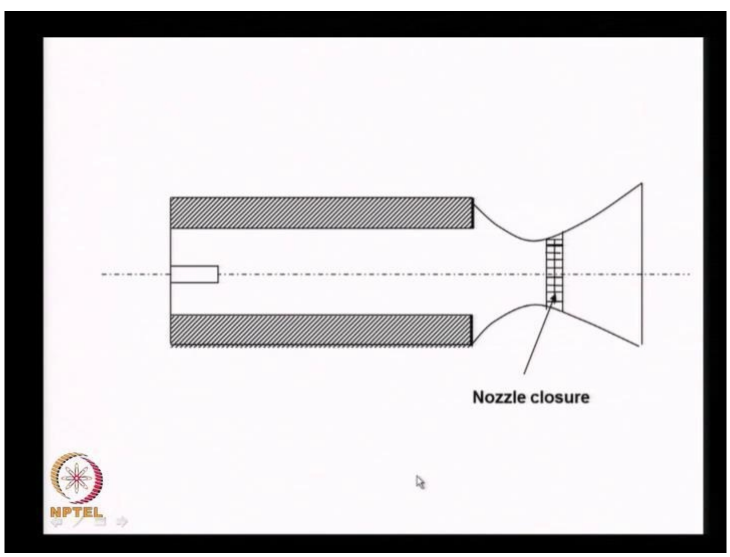

We also said that the hot gases must be contained within this port volume or cavity to ensure ignition. We use a nozzle closure and the moment pressure builds up well this is ejected out. And therefore, flow through the nozzle gets started after we make sure that the ignition takes place in a chamber. The port volume is sort of enclosed with this nozzle closure. It is made of some ablative material and is bonded over here by glue. The moment pressure is developed in the port volume, it is pushed out. We use such nozzle closures in liquid propellant rocket engines also.

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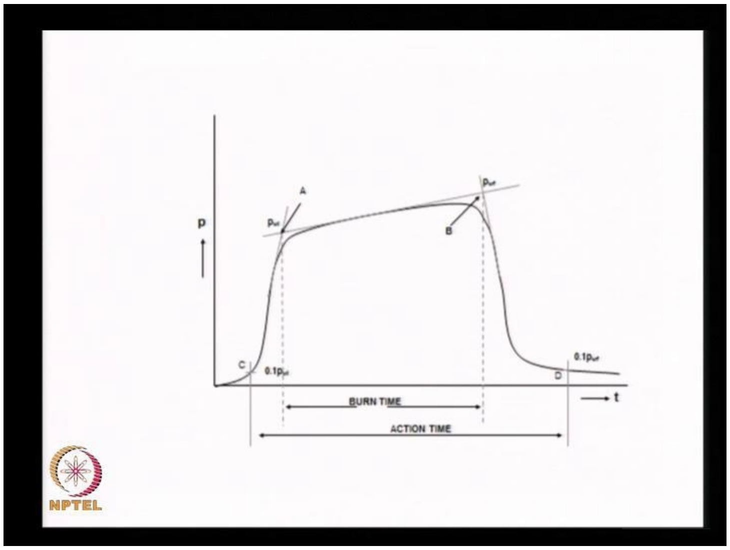

We talked in terms of burn time. Two tangents intersecting; this is shown for progressive case: A to B is the burn time. The time of one- tenth of the pressure at ignition to one-tenth of this pressure at burn out over here, is what is the action time. Well these are all about the solid propellant rockets.

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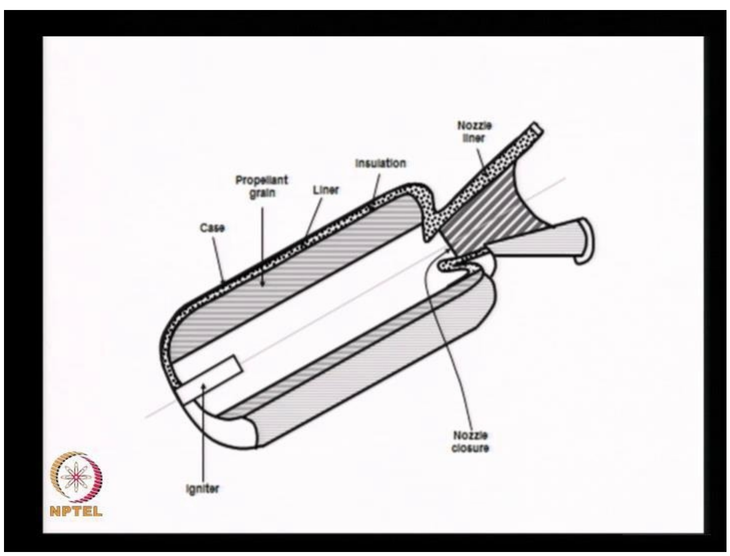

Now having done all this, let us put all components of a solid propellant rocket together in a single figure. What are the components of a solid propellant rocket? Well propellant is basic and it is contained within an insulation or a liner. After this insulation we have another liner, make sure that it is compatible with this insulation such that heat does not get conducted and weaken the motor case or cause the case to burn off. Therefore, we have a propellant, we have a case, we have insulation and liner is also a form of insulation. And then we have a nozzle; the nozzle could be sunk into the propellant and it could be made to flex. We have seen when we talked of nozzles. We have a nozzle closure. We have an igniter, which could be a pyrogen igniter or a pyrotechnic igniter. Well this is all what a solid propellant rocket consists of. And we said, the solid propellant rocket is called a motor because there are no moving parts in a solid propellant rocket. Having done all this I thought let us review two practical problems, which have been encountered, during the history of development of different rockets. And I just choose two of them, because all of us would have heard of these problems and let try us clarify what really happened.

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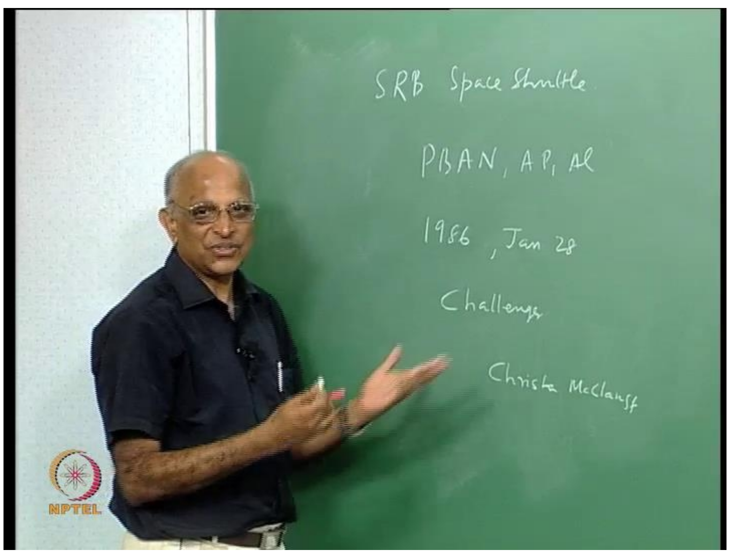

One is we talk in terms of solid rocket booster for space shuttle. Our interest in this was because it is the world's largest solid propellant rocket. It uses PBAN, polybutadiene acrylic acid acrylonitrile as a propellant. This is the fuel binder. Of course, it contains AP and large amount of aluminum as in all solid propellants. And what was the problem? In one of the shuttle launches in 1986 in the flight Challenger the motor misbehaved. And the entire crew of 7 died. It was the first time that they took a civilian into space, they took a school teacher along. What was the problem?

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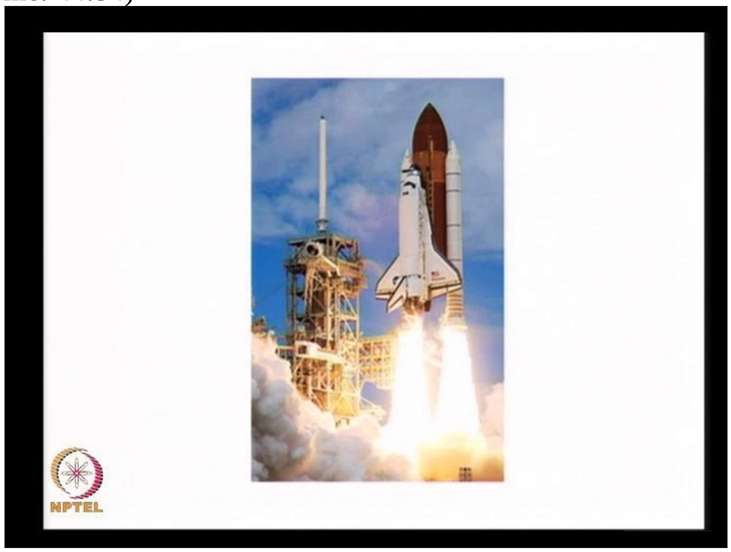

Let us try to understand what really went wrong. Well this figure shows the space shuttle. What does the space shuttle consists of? It consists of a central engines which are hydrogen oxygen cryogenic engines, there are 3 of them here clustered together and they burn simultaneously. And behind the space plane we have a huge liquid hydrogen tank and at the bottom of it you have the liquid oxygen tank, this is the huge liquid hydrogen tank you need a huge tank, because liquid hydrogen is not very dense. You have two solid rocket boosters. First what is done is these 3 liquid engines fire, it is ensured that adequate thrust is developed, because you can always switch on and switch off a liquid propellant rocket. And once it has developed a particular thrust, the two solid rocket boosters are fired. Mind you this what we said is around 3.8 diameters and around 40 meters in height. They begin to fire and in this particular launch it happened on a cold day.

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The temperature of the ambient was around minus 1 degree; it was around in the morning around 8 clock or so that the launch was to take place. The previous night the temperatures went down as low as minus 15 degree Celsius. And this shows the perfect launch at take off. It takes off beautifully, but then after sometime around 0.6 seconds after ignition of the solid rocket booster in this region in the right side engine little bit of gas was found to escape.

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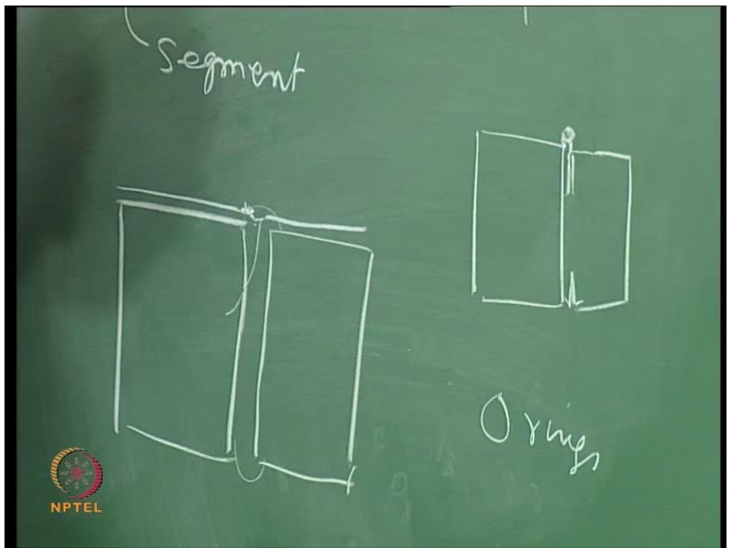

Whenever we have such huge boosters, the construction of the propellant block as a single grain is very difficult. The propellant is cast into different blocks and then assembled together. Each block is known as a segment. And now therefore you make small segments of the same diameter and the solid propellant segments in the case of space shuttle consists of something like 6 segments. And what is done at the factory where in these segments are made? Few of the segments are assembled in the factory such that it is still transportable. The final segments are assembled together at the launch site. How do you assemble the segments? We have the case over here, you need to make sure that these two are put together or joined together such that the no leakage of high pressure high temperature gas is possible once the huge motor ignites.

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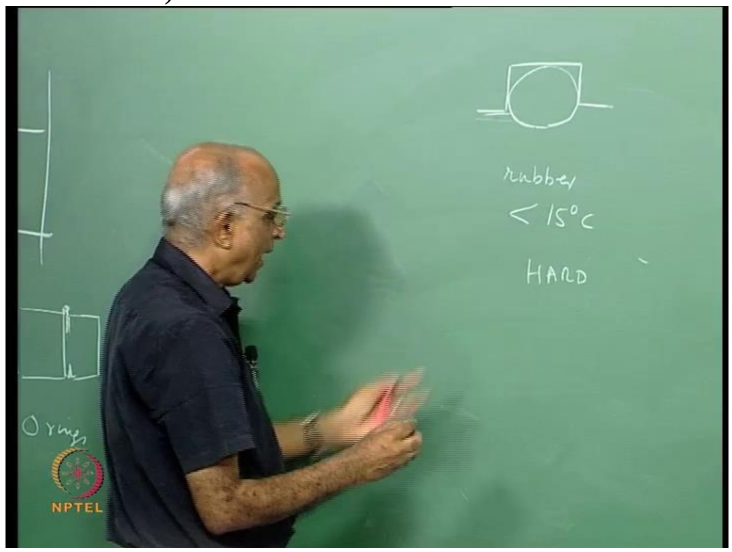

Between one segment and the other may be have to put something some insulation, then we have to put the other segment over here, this has to be joined together maybe I should be able join it in some form at the interface. And how is it joined? We use ‘O’ rings. Let us try to make a sketch of how the O rings function. See how do you assemble an ‘O’ ring in a groove? We insert the O ring in the grove. When we assemble the cylindrical face of the other segment the O ring being flexible, it flows and makes this junction to be air tight or leak tight. And therefore, 2 O rings are used and these O rings are of rubber. The rubber O rings which were meant for this had not been tested for temperatures less than 15 degree Celsius. The previous night was cold this particular launch was on hold for some time. And therefore, what happened was that the O ring which is resilient at ambient temperature becomes rigid and hard and when it becomes hard it does not seal the joint properly and allows the gas to flow by.

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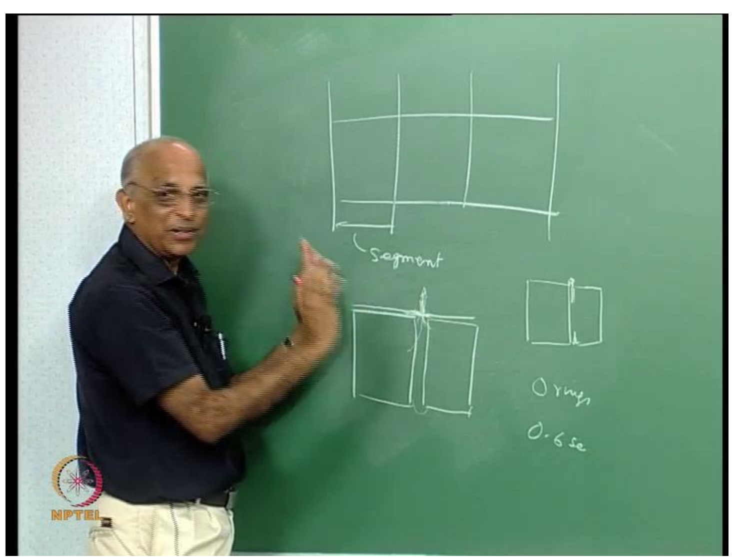

And therefore, at the segment joint some little bit of the high temperature gas from the chamber begins to leak. And this was observed within 0.6 seconds after ignition. This was observed and some minute amount of gas was beginning to escape. But you know that the propellant used is highly aluminized. Therefore, what does aluminum oxide do, it goes and blocks the leak path and prevents any further leak. The motor is still safe it keeps on firing further and further.

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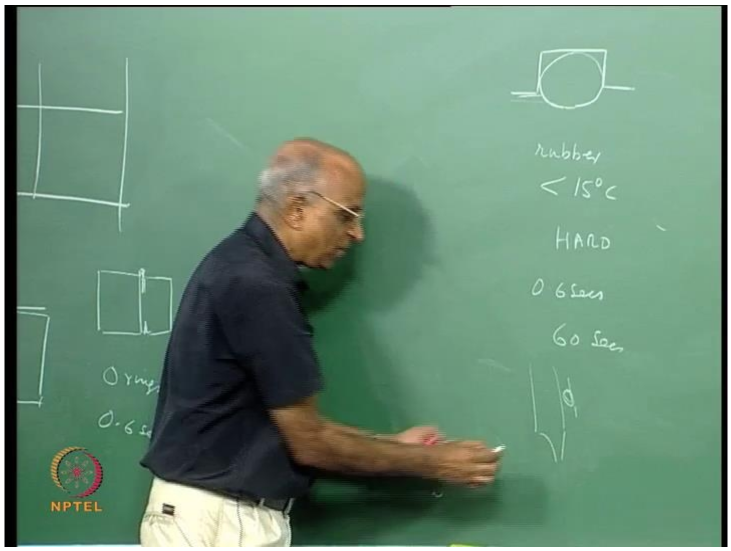

From 0 to 0.6 seconds at which the "O" rings have failed up to something like 60 seconds or 62 seconds, the flight or operation of the solid rocket booster was perfect. The aluminum oxide has blocked the leak path and the chamber remains normal.

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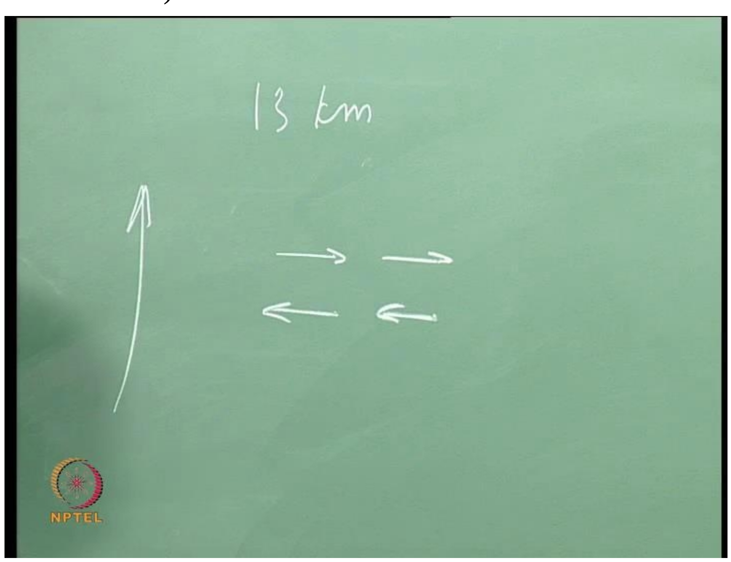

It then goes through the atmosphere at around may be something like 13 kilo meters height Whenever we fire a missile or a rocket and it goes up through the atmosphere, we have wind in a particular direction. But in some locations we have bottom layer of wind in the opposite direction to the next upper layer. We called is as a wind shear. Some layer of wind moves in this direction the adjacent layer of wind moves in the opposite direction. When the space shuttle is moving up let us again put the events together. Now the vehicle is moving up, and what is happening? It goes though wind shear, it get’s shaken and therefore, at that point in time the accumulated aluminium oxide which hold the leak gets breached.

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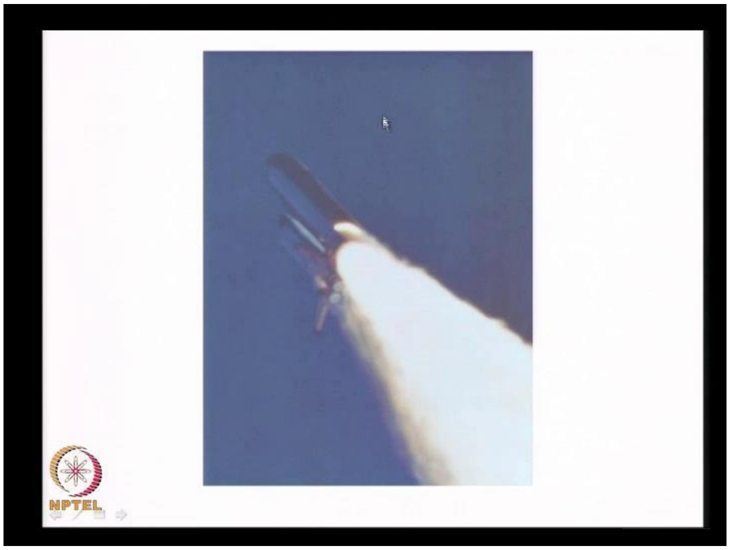

At the bottom on the right hand side the leakage path opens out some flame comes out. And when this flame comes out it hits against one of the attachments, which secures the solid rocket booster to the main core rocket. And that gives way and the solid rocket booster comes out and it gives a thrust in some other direction. In addition, the flame hits against what we said is the hydrogen tank, ruptures it and spills the hydrogen. This happened at a height of around 14 kilometers. And well the hydrogen mixed with air and there is a huge fire ball and the entire mission is a failure.

Therefore, we see the corrective action of aluminum oxide in sealing the hole or the leak path which is disrupted by the wind shear. In fact one of the recommendation is whenever you use a pyrogen igniter we should not use considerable aluminium for the propellant as the nozzle will get clogged.

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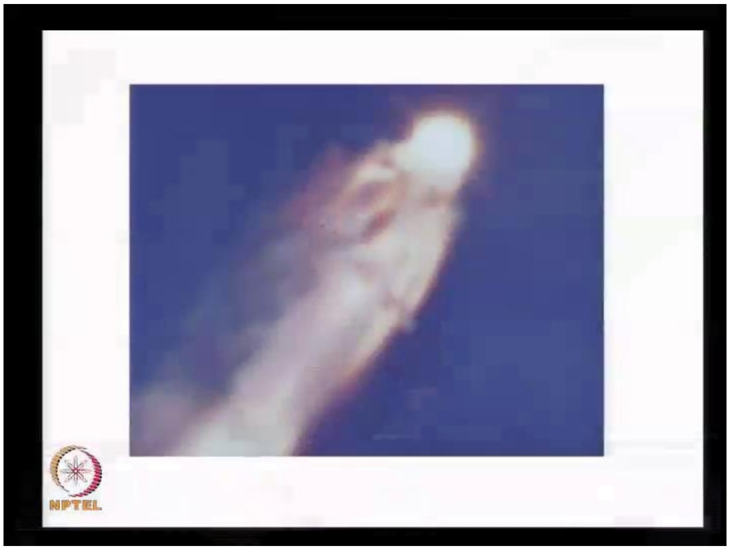

But in the case of solid rocket boosters it helped. But the failure was because of the O rings which were not doing the job and the wind shear which dislodged the sealing by aluminium oxide..

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We will now consider one last example, which is interesting. We will perhaps cover the details of when we look at instability in rockets.

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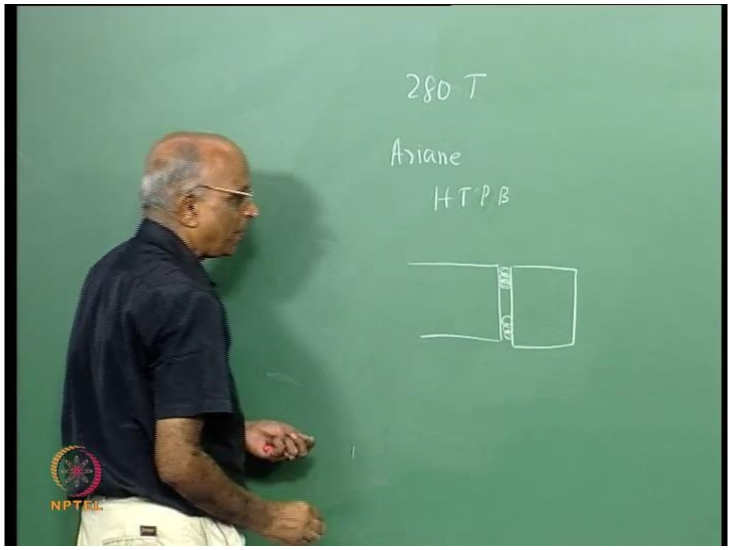

You know this example relates to the second largest solid rocket motor. We just picked on these two; while the solid rocket boosters of space shuttle have something like 500 tones of propellant, this second biggest rocket has about 280 tones of propellant. This is used in the launch vehicle Arianne. Arianne is a French rocket. And the solid propellant rocket uses a HTPB based propellant, hydroxyl terminated polybutadiene. And in this particular case, what happened is again being a large rocket with a number of segments. And how do you assemble the segments? Well in between the segments, we put glue or some inhibitor, join it together so that it is perfectly leak tight.

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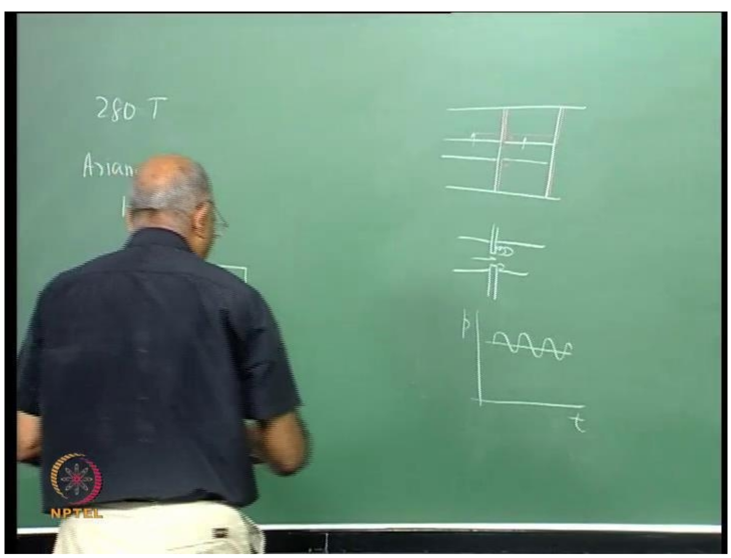

And let us now consider a segment joint. We have one segment over here; this is the inner diameter; we have the next segment coming over her. We have the inhibitor or joining glue over here in between. Now when the propellant burns the propellant burns fast where as this fellow viz., the inhibitor does not burn as fast. Therefore, after sometime we have the inhibitors standing like this over the propellant surface. The flow of the gas in the port is obstructed and eddies are found. These eddies in the flow have a characteristic frequency and these disturbances get amplified and the thrust instead of being steady starts oscillating. And the oscillation is because of eddies that are formed, because of the projection of the inert in the propellant. Well we have this protrusion here, which causes the pressure to oscillate. We will study the mechanism of oscillations in the chapter on combustion instability. Well, this is all about solid propellant rockets; maybe we should try different problems.

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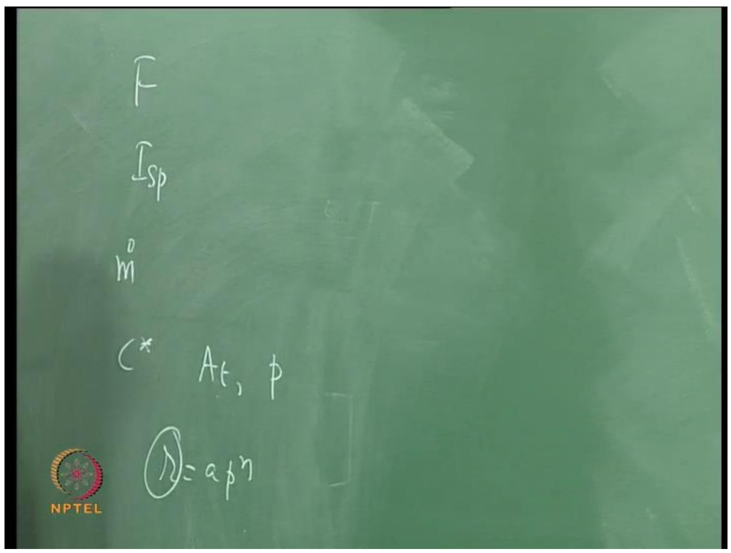

To sum up, if we are given the thrust of a solid propellant rocket, which is to be made, and given the specific impulse of the rocket, we can find out what is a mass flow rate required. We can use the C* of the propellant to find out what is the value of the nozzle throat area At. We choose the pressure of operation of the solid propellant rocket p. And the burn rate of the propellant is known; $r = ap^n$. We can find out the burn rate and then solve for the burn surface area. And in the assignments, I have given you something like 10 problems, which you should do. In the next class we will start with liquid propellant rockets.