Indian Institute of Technology Madras
Presents

NPTEL
NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

Aerospace Propulsion
Solid Rockets – Performance

Lecture 26

Prof. Ramakrishna P A
Department of Aerospace Engineering
Indian Institute of Technology Madras

In the last class we had seen that what is the value of n for which the propellant will operate stably right in all the analysis that we had looked at till the last class we had looked at basically determining the burn rate in a strand burner or a Crawford bomb right. Now a rocket motor depending on its application if it is in a tactical missile or a launch vehicle can be very large compared to what you do in a strand burn right strand burner you essentially take a few grams of propellant and measure the burn rate.

Now in today's class let us look at what are the parameters that are going to change when we go from this small strand burner test to the actual motor and how do we account for it in some sense okay, firstly if you remember I had written that burn rate.

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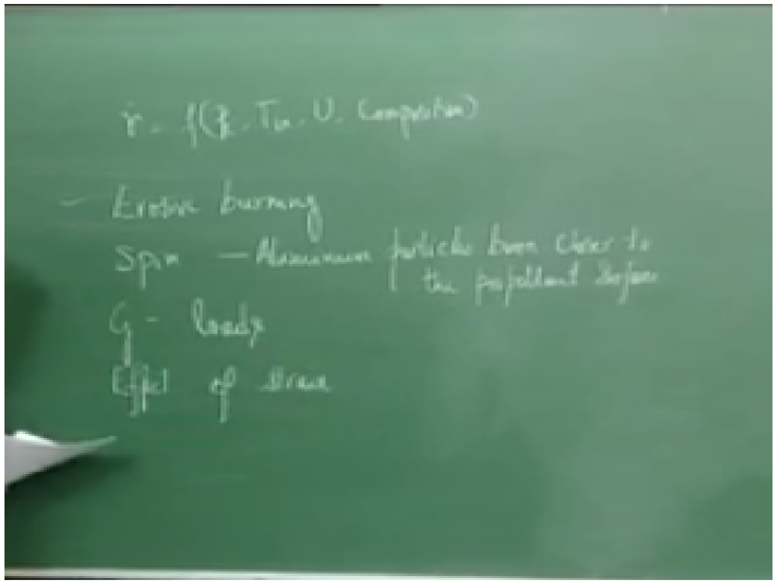

R. is a function of chamber pressure initial temperature cross flow velocity and Composition this part of broad cross flow velocity we are going to look at it in a little more detail this is going to cause what is known as erosive burning, that is if you have a rocket motor whose pore diameter is quite close to the throat diameter then it is going to be subjected to arouse you Bernie we will discuss that a little later in the course, so this is one part we will not be able to measure in our strand burner tests okay.

So the first thing that we are not able to look at in a strand burn test is erosive burning okay that is going to be different in actual motor compared to this there are some small motors which has spun at some high rpm in order to make them go straight okay, these are probably in tactical applications only tactical missiles only they are spun at a high rate so that they go straight. Now what happens in such a case especially in an aluminized propellant is these aluminum particles are subjected to a centrifugal force.

So they tend to burn much closer to the surface, so therefore the burn rate increases strand burner you do not have that so that is something that you have to account for then what are the other things that you think will change from the small strand burner to the actual motor, chamber pressure you can essentially hold it the same as the water is going to be there in the large rocket motor that is not something that is bound to change yes g-loads but that is not going to be large in both the strategic missiles and launch vehicles because if you look at it there accelerations go from somewhere around 1.6 24 GS they could be of significance in tactical missiles these come on because they are subjected to enormous accelerations right.

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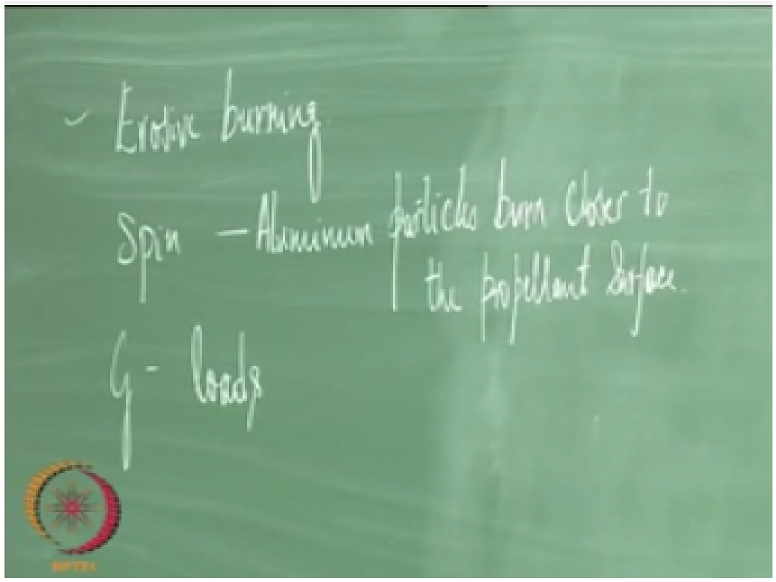

Then as a consequence of this and also if you look at the entire mess a missile or launch vehicle it is a large mass of propellant right, there are regions which are subjected to strain because of its own weight those things not been kind of included in our desks in the Crawford bomb right, so effect of right. So these are the things that change from our Crawford bomb test to the actual test, typically it is seen that the burn rate variation from a Crawford bomb test to an actual test is somewhere around less than ten percent somewhere around a 2 7 to 8% in it is still vital primarily because if you look at the GSLV kind of configuration or the Aryan 5 kind of configuration or the Space Shuttle conversation you have two large solid rocket motors right.

Now if they do not complete combustion at the same time you are going to have a tremendous side force which could topple the entire vehicle which is something that is not desirable or you need to have a tremendous control force to overcome this which is also not easy to overcome because the thrust produced by this motors are very large, so that is something that is very important to note that there are changes to burn rate from The Stand crest Crawford bomb test or the Strand burn attest to the actual motor.

And then there are kind of thumb rules to tell us what is this difference going to be people with experience will know that if they conduct the burn rate in a Crawford bomb and then as an intermediate you have something known as a ballistic evaluation motor and then the actual motor so if you have the data for all these three then depending on the Crawford bomb tests you can then what they do is while making the propellant they take a portion of the slurry and get the burn rate of the slurry and if the burn rate is different than the add the suitable burn rate modifiers to get it back to the level that they wanted to be.

So that they know what is a priori before the cast what is the burn rate right as I said in some tactical missile applications if you wanted to go straight there has been stabilized you know bullet has spun at tremendous weights as to go make it go straight otherwise aerodynamic loads will make it go in a different direction right. So you wanted to go straight then you need to spin it is called as gyroscope stabilization that is if you still spin at some very high rates the shells are spun at something like eighteen thousand rpm if you spin it at that rate this is like a cycle week as long as you are pedaling it you would not follow rIight even if there is a force that tends to destabilize you right.

If you look at the cycle it is like an inverted pendulum you can model it as an inverted pendulum it's a mass that is there at some height right and inverted pendulum is you know is very unstable small disturbance can make it change its stability. So there what you do is you spin the wheel so that you get that stability unless you are moving forward you cannot stabilize yourself right, so in the same way if you spin it you can then make it go straight and coming back to the topic we had also looked at certain equations for pressure in the last class right we had said that the chamber pressure P_c is given by fine.

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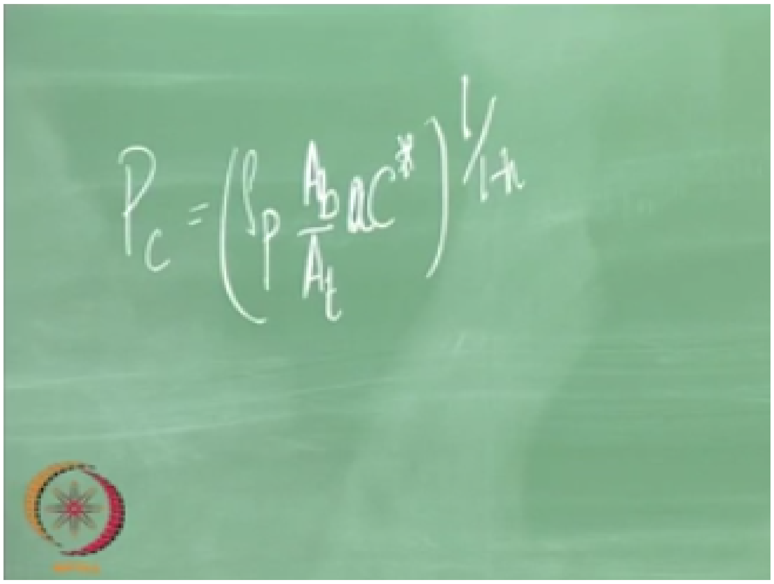

Now we can also add trust define trust in a similar manner right we can use trust we knew f = CF pc 80right. So now if you use this definition for pc here you will get f is equal to CF ropey okay, so this sorry this has to be a tease this is plus one this has to be minus okay because this is in the denominator. So which you can simplify as okay.

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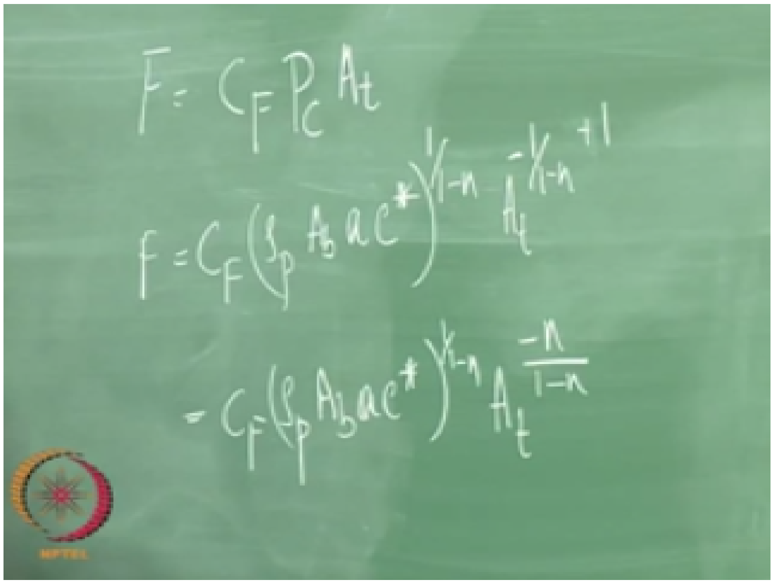

So f you can define it in this fashion right, we also know that the term a has embedded in it the temperature sensitivity part right. So we can use that we knew that a was a0 x exponential loop. So if we plug that into this equation and this equation we will get the variation of chamber pressure and trust why are we doing all this let us try and estimate if there is a marginal change to let us save the burning surface area or the throat area or changes in temperature what is going to be the effect on thrust and chamber pressure okay.

Why is this important first thrust part I kind of explained it in a sense if you are looking at the launch vehicle part you do not want the thrust to be different in the two motors that is j cell with class motors even otherwise you the entire launch vehicle if you take a look at it should take the satellite to the required orbit height and it should give it the required velocity if there is a short fall in some cases they do use some liquid engines to take care of that okay but if you are looking at a missile then again you have this problem that even though temperatures are varying widely you still want to be able to hit a particular target right.

So you need the thrust to be estimated appropriately, then if you look at the chamber pressure part the if you look at all aerospace systems the factor of safety is going to be very small right it is somewhere around 1.6 to 2.2 so if your factor of safety is very small then your margins are also very small right due to changes in temperature if the pressure exceeds by a large fraction then you could have the motor bursting out right you would not want that to happen, so we need to have some estimate of what is going to be the change to pressure and thrust if there are small changes to burning surface area or throat area and temperature okay.

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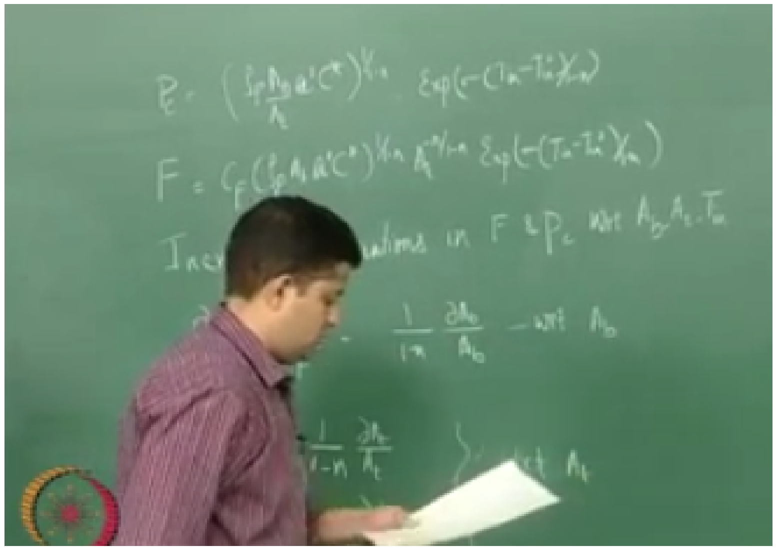

So that is the reason we are trying to plug in all this into this equation so if you plug in the a variation also you will get Pc into exponential of and similarly F will also have you can expand a in terms of this so f will be okay, so we included all the variations of a b a t and initial temperature right.

So let us now do something known as an incremental analysis wherein wheels see if there are small changes to the either a b a t or initial temperature what will be the corresponding change in terms of chamber pressure and thrust how do you do this very simple take a partial derivative right if you are looking for burning surface area take a partial derivative of chamber pressure or thrust with respect to the burning surface area so let us do that f & pc with respect to a b a t and initial temperature okay.

So what is the with respect to let us take firstly A_B what is the variation of a B with respect to or what is the variation of Pc with respect to A_B so you get do pc by if I take p see if I / pc this is the same as a bee appears in the same fashion in both these equations right, so the partial derivatives will be the same if I take the partial derivative and /the actual value then I will get the incremental change.

So this will be the same as $\partial f / f = 1 / 1 - n$ into okay, and if you look at a t again a t appears in the denominator here and it has a design a different power here, so this is with respect to A_B then for a t these two will not be the same so here it a t is in the denominator, so it will have a negative sign, and lastly if we look at how these two change with initial temperature I will call TI n - TI n 0 as Δ TI n okay.

Then both of them are change in the same fashion if you look at this both of them are raised to the exponential of this value, so both of them will change in the same fashion, so you will get so we have been able to look at what is the incremental change to chamber pressure and thrust in terms of changes to burning surface area throughout area and temperature. Now let us look at how each one of these will vary if you look at burning surface area right burning surface area is the area that is seen by the flame, now if you look at a rocket motor this propellant can be extruded or cast either process you will have some kind of imperfections that is you will have somewhere cracks blow holes right.

So now if the flame comes to this position right let us say the position is somewhere here or if it is somewhere here it sees an additional surface area right suddenly an additional surface area is exposed to the flame okay, so the burning surface area changes because of imperfections in the manufacturing process.

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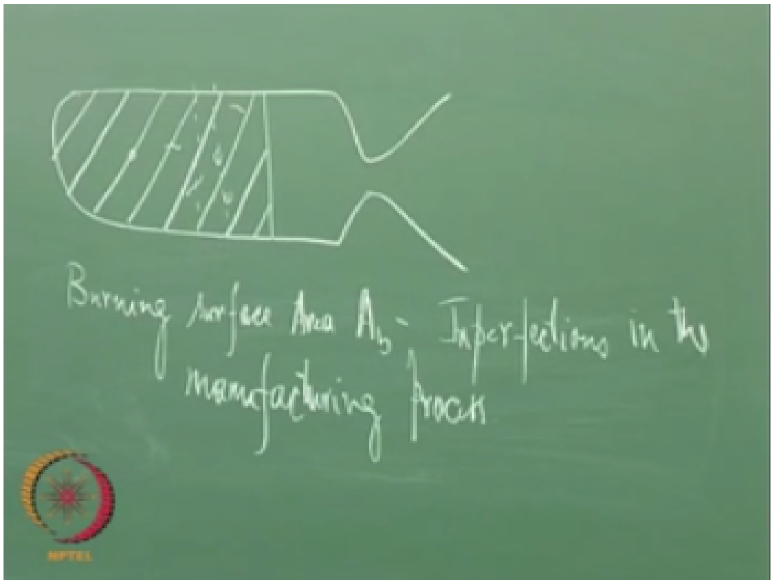

These could be you know propellants are made in one place and then move to another place to the launch pad right, so during the transportation it could the damage could get could be accentuated that is it could be increased and also if you are looking at higher stages having a solid rocket motor due to the enormous vibration loads that come on the propellant while it the first stage is burning let us say then the these imperfections could also be increased there okay.

So we now know how burning surface area will change how do you think the throat area will change due to erosion of the nozzle you could also have deposit okay if it is a heavily aluminized propellant in some cases it is seen to have a deposition also so either case is possible erosion of throat and as well as deposition basically mean most cases it is erosion is the more predominant from phenomena.

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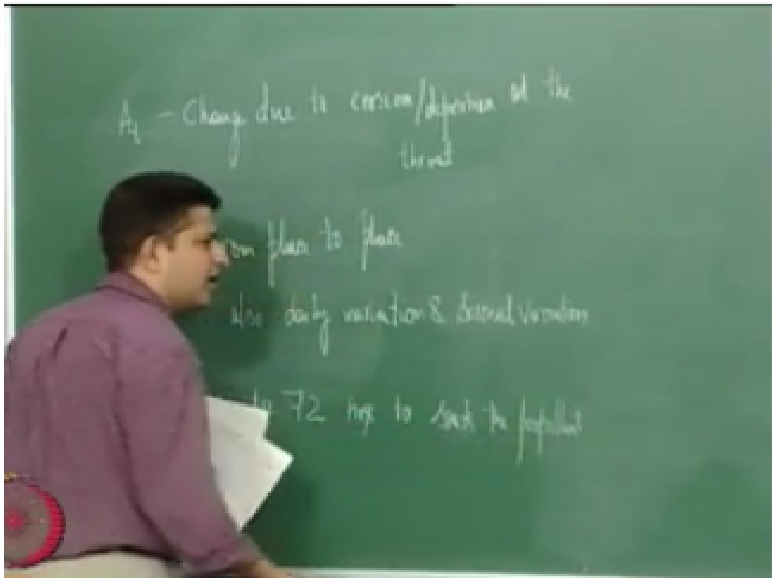

Typically this throat erosion or deposition is a function of the burn time if you have a large burn tan right then you could have something like eight to ten percent increase in the throat area if the throat area increases in the pressure will drop okay and you are also in a sense reducing the area ratio for the supersonic portion right. So it hits you in two ways one is drop in pressure and then the ISP will change because of drop in pressure one and then again because of the expansion ratio being changed okay.

The burning surface area changes if you know if you are trying to make a large rocket motor let us say of the glass of gslv mach3 the first stage which is a200-ton propellant okay as I said it is very difficult to make propellants without imperfections right there will be some amount blowhole some amount of cracks I think so what they do is they do a detailed non-destructive testing that is they take ultrasound images of the propellant and study it and find out where the imperfections are how large are these imperfections okay.

So which is what makes it very expensive because if you have to do the entire rocket motor test it takes a lot of effort and time and you also need those kind of facilities to make once the entire rocket motor has been made and the reason why in one sense they make a segmented grayness let us say you are casting 200 motors in one go if you make the entire motor and if you realize that the imperfections are only in certain portion then you have to redo the entire 200 tons right so it would be better if you can make it in smaller segments, so that you know you can take out the portion that is bad and then replays only that portion okay.

But if you have also too many segments then your reliability in some sense goes down and you are also exposing it to in some sense combustion instabilities because you will have some protrusions coming in because of the liner and that is something that you would not also want so it is in essence give and take between these two okay, now lastly how much does the temperature vary the initial temperature initial temperature varies from place to place and also daily variation and seasonal variation.

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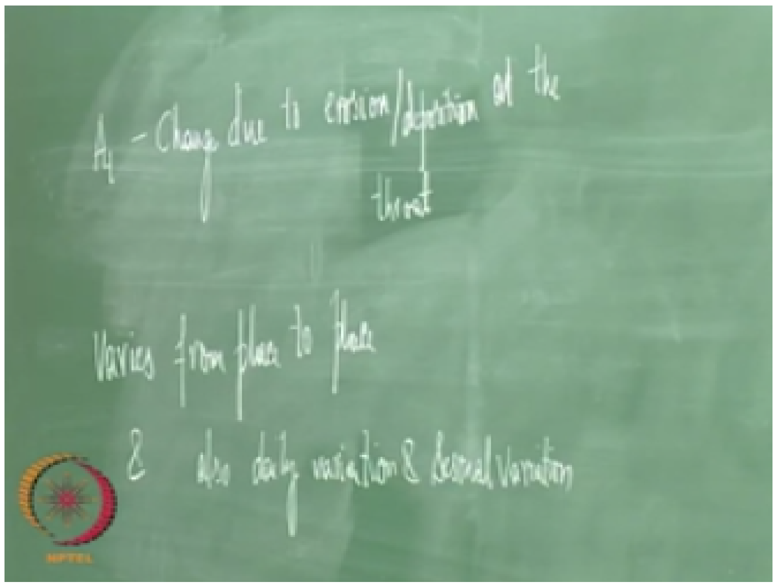

Even in a single place are depending on the season temperatures can vary and depending on the time of the day temperatures can vary one good thing for us s most of the solid propellants are very bad conductors of heat, so it takes them long time to really sense what is happening on the outside. So typically take something like depending on the size of the web thickness take something like 24 to 72 hours to soak the propellant that is if the ambient temperature changes let us say from 27^0 to something like zero and if it is there in that condition for a very long time only the entire propellant go to that temperature otherwise you will have a gradient even in the propellant okay.

So now we have kind of got these equations let us liniearized them in a or let us take a small variation in a b these are non-linear variations let us take a small variation in a b liniearized these equations and find out what is the change in pressure and thrust okay.

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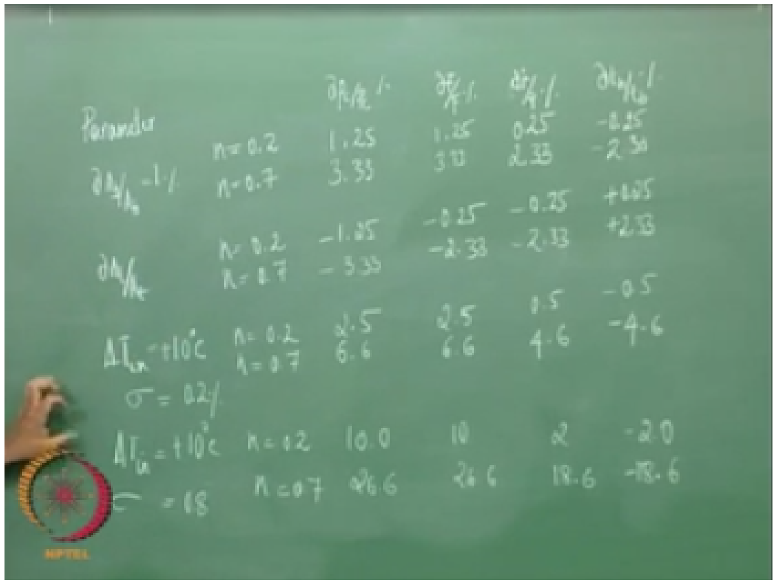

So if you do that I have taken two cases wherein one as a small σ one as a large σ I will also take for each one of them what happens when n is small and when n is large just one important thing if you look at the sign of these incremental changes both the changes to burning surface area and initial temperature have a positive sign okay whereas the changes with respect to throat area have a negative sign now as I said also we will take two cases for n n being small n being large ah this is incremental change in burn rate and correspondingly in Creed mental change in the burn tank we know that changes in pressure and burn rate are related r dot is equal to a PC to the power of n.

So we have used that to we can use that to calculate this and if you know the burn rate you can also calculate the burn time now if you notice this as I said earlier this sign of this will be different from the other two right so all this is with minus sign whereas all this is with plus sign, so the changes in burn time will be the negative of the changes in burn rate right so notice that the worst case would be if you have a large σ and a large n then your changes to chamber pressure with 10 ^{0} change in ambient pressure can be of the order of twenty-six percent right which is pretty significant and thrust will also change by the same margin.

So in a sense it is very important to have propellants that have low n and low σ P right, but what do we do if we cannot have them right there is something that we want sometimes we are not in a position to be able to achieve that so what is the next big thing that we can do as an engineer only thing is try and control it in some fashion right as I said earlier if you look at this throat area is in a has a negative sign compared to the other changes right one way to look at it is if you cannot have a propellant with low end and low σ if you look back you will find that homogenous propellants are always are going to have higher and higher σ right compared to composite propellants.

So if you have such propellants which are mostly going to be used in tactical missiles what do you do you can look at this and in some sense if you can change the throat area depending on the condition then you will be able to achieve or you will be able to minimize the changes in initial temperature because this has a negative sign and that is what is done in certain missile applications you will have a plug.

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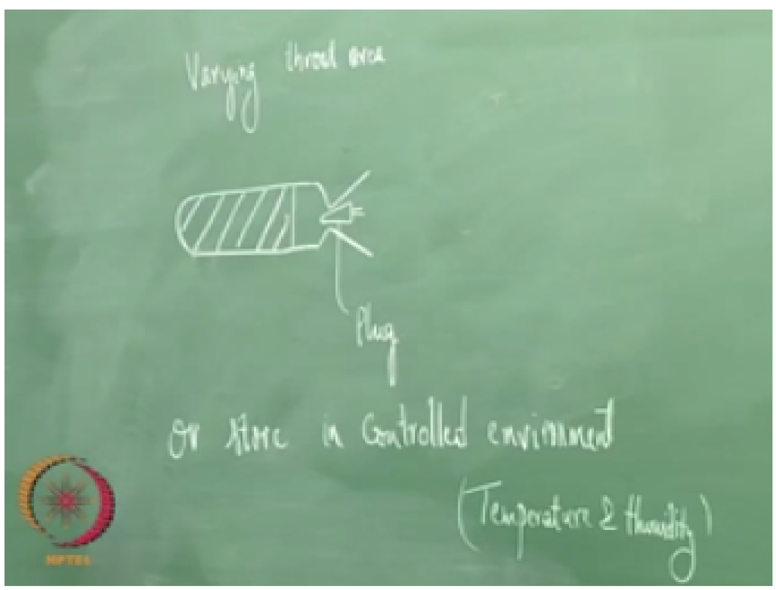

So if you have a plug like this of whose diameter changes from one end to another that is you use a cone and if you are reading this in some fashion then you can move it in or out depending on what is the requirement right, so you will be essentially changing the throat area to accommodate for changes in the initial temperature right. The other way to overcome this is let us say we are in a position to store these missiles in a controlled environment okay and as I said earlier these are very poor conductors of heat.

So it will take them a long time to soak to the ambient temperature, so if you can maintain some of these missiles in controlled environment then and you are able to use it in the next couple of hours let us say then these effects would not take too much of a toad right. So one way is to have a best is to have a low end and low σ P if that is not possible then have something where in the throat area is changing this cannot be a solution for a large missile application primarily because this plug is exposed to high temperature gases and if the burn time is very large it will tend to burn itself out which again will dramatically change things do not want that either.

So these are applicable only for small tactical missiles with small burn times okay not for large boosters or missiles and as I said if you cannot do this either then the only way is to store it at a controlled n1 store it in a control and one these are not possible for very large rocket motors also large missiles you cannot have them stored in a controlled environment and then be able to move it to the launch pad within a very short time.

So what is done in such cases is you will have a small liquid rocket motor attached to the payload which will make up for any loss in thrust which you can cut off at any stage so that is what is done in missile applications in order to overcome this problem those small liquid rocket motors are called as velocity termination packages okay, so if you do not have the required velocity at the end of it that will make up for it by burning for a short time okay.

So in the next class we look at how to go about designing a grain of a solid rocket motor okay, what are the things that we need to keep in mind how do we get the required trust time curve if we know a propellant has certain burn rate and okay, so we will meet in the next one thank you.

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K.R Mahendra babu.
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S.Pradeepa
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Camera

Selvam
Robert Joseph
Karthikeyan
Ram Kumar

Ramganesh
Sathiaraj

<u>Studio Assistance</u>

Krishnakumar
Linuselvan
Saranraj

<u>Animations</u>

Anushree Santhosh
Pradeep Valan .S.L

NPTEL Web & Faculty Assistance Team

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