Rocket Propulsion

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Lecture No. 11

Area Ratio of Nozzles: Under – Expansion and Over – Expansion

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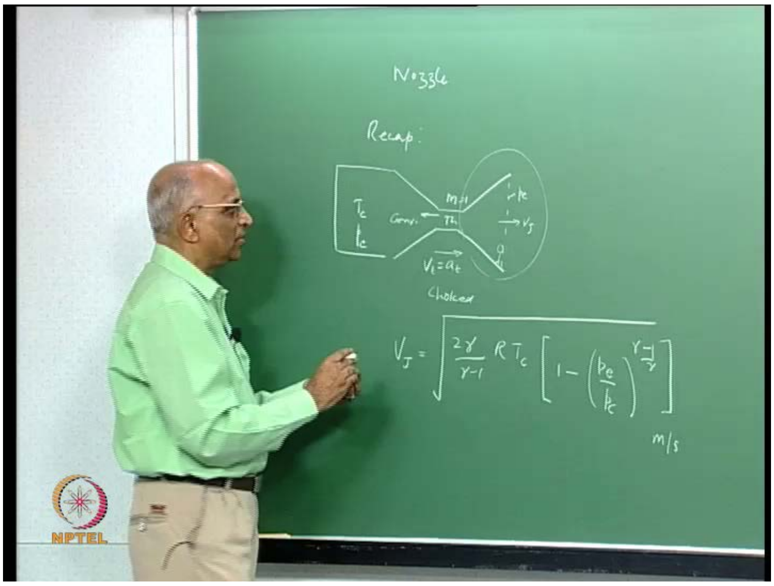

Well good morning. We will continue with the portion on nozzle, what we do today is we will find out what is the effect of area ratio we will define area ratio. We will also find out how the nozzle operates at different attitudes and look at some typical results. But, before doing that lets quickly recap where we so that we can connected to with what we are going do today all what we told in the last class was a nozzle, if we need to have a high jet velocity means to have a convergent may be it should have a thought for which mach number is equal to one and then I should have a divergent. We were very clear about the throat, we said it is the place where the velocity is sonic that means the thought velocity is the sonic velocity may be V t is equal to a t.

We also told ourselves any disturbance here, suppose I stand on nozzle here and make a loud noise or I do any disturbance this disturbance cannot enter the convergent and therefore, the chamber over here the reason being the velocity here is equal to the velocity of sound in the throat and is greater than the sound velocity in the divergent and any disturbance, which generates downstream can only can cannot travel here because the speed here itself is sonic and therefore we told ourselves any disturbance downstream of the throat cannot enter the chamber.

And therefore, the sonic throat essentially decouples the convergent and the chamber from the downstream portion this is because a disturbances travel at the sound speed. Second thing we also told that the throat is choked. In other words, we told ourselves that for the given mass flow rate I can have a maximum velocity, which corresponds to sound speed at the throat and if I want to if I have higher pressure or if I suck it at lower pressure I cannot exceed this condition that means the throat always will have mach number equal to 1 or the velocity here should be the sound speed. I think these definitions are important.

We also derived an expression for the jet velocity at the exit, which we derived as V J as equal to 2 gamma divided by gamma minus 1, we will write in terms of the specific gas constant R into the temperature within this chamber into we had something like the expansion 1 minus the exit pressure that is the pressure at the exit over here divided by the chamber pressure here P of the chamber over here and this P e by P c to the power gamma minus 1 by gamma and this was under root and this we did not even consider the convergent divergent shape, we just said that if the chamber pressure is P c if the exit pressure is P a then you have the pressure ratio if coming this is the temperature in the chamber and this is how we derived the expression for m j, which was so many meters per second it is all right.

And what we started with a vent, we derive the velocity and then to look at the shape of the vent it was necessarily for us to have a convergent followed by the divergent such that if I were to now plot.

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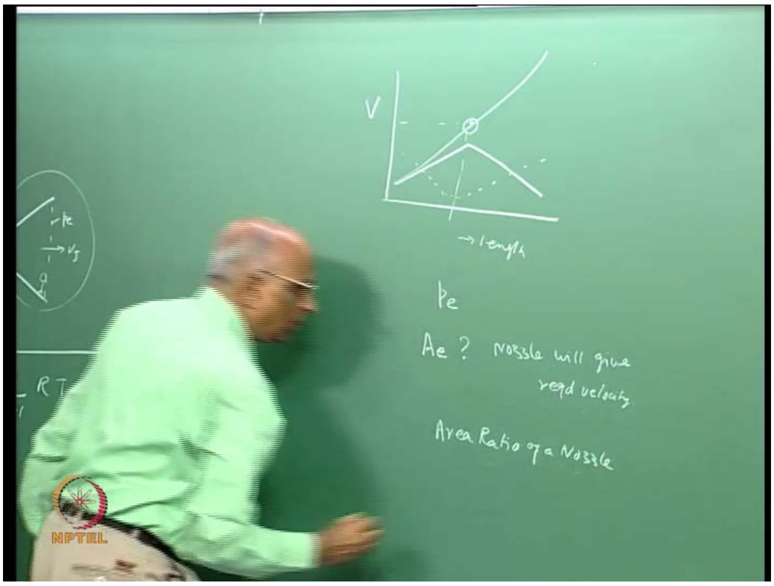

The velocity of the gases as a function of the length of the nozzle mind you along the length of the nozzle initially I have a converging shape then I have a throat then I have the diverging shape this is I get the sonic velocity and therefore, the velocity will keep increasing along the nozzle.

The moment I have at the throat the velocity less than sonic the velocity builds up and thereafter the velocity founds. Therefore the necessity to have mach number one at the throat was essential, right. I think this we must remember all the time. Having said that, now in today’s class, we will try to see instead of mentioning that the exit pressure is P e now after all have to realize a nozzle, can I put it in terms of number let say the area ratio at the exit will be a e and therefore, what must be the area ratio a e such that the nozzle will give me the required velocity and that is I want to do today.

Let me repeat again, see when I realize a hardware I do not know the value of P e; all what I know is I must have a configuration like this, I must know a diameter over here, I must also have the diameter at the exit or rather the exit area ratio. Therefore it becomes essential for me to define something like area ratio of a nozzle to be able to give me the value P e such that I can get the jet velocity or rather I want to know the configuration.

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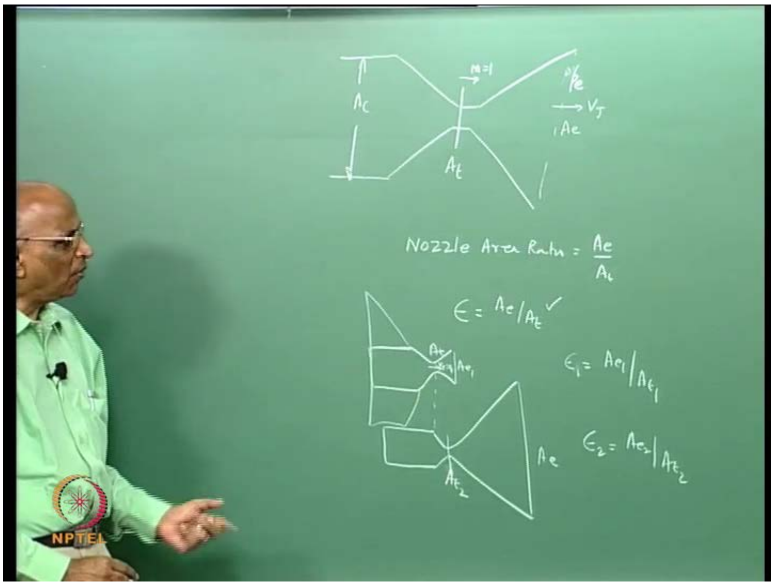

Let us put it this way, I have convergent, I have the throat, I have the divergent. I want know what will be my exit area here such that I can get the V J whatever I want, I want to find out the expression for the jet velocity in terms of a diameter or a area ratio rather than put it in terms of the value of the pressure at the exit, which we called as P e. To be able to do that we tell ourselves well I am looking at the exit area, I would like to define the area at the throat, because I know that at the throat the mach number is always equal to 1, therefore I can define it as a critical or a particular area for reference and I call the nozzle area ratio as equal to the exit area divided by the area at the throat this is by definition.

In fact, you know initially all of us tend to think, if I have to define something like an area ratio maybe I should in terms of the area of the chamber over here and related to the area at the exit, but whatever be the area here the reference is the throat because that is where the velocity is always equal to the sound speed or mach number is one, therefore we define the nozzle area ratio as the exit area divided by the throat area and it is denoted by epsilon and epsilon is equal to A e by A t, is it okay. Having said that, area ratio is A e by A t, I want to derive an expression how the area ratio will affect the jet velocity or how should the performance of a nozzle be link to the exit area ratio.

Let me repeat the problem such that it becomes little more clear. Supposing, I have a small rocket let say, I bring it to the throat mach number one, I could have a small area ratio or I could also have a same rocket in which now I again draw this one over here, I could have a very large area ratio and how do I find out the compare the performance of an area ratio, which is A e 1 with area ratio A e 2 and if the throat area is the same in the two cases A e by A t 2, I have area ration 1 is equal to A e 1 by at 1. In the second case, I have area ratio is equal to A e 2 by A t 2. I want to compare which one gives me higher velocity, I want to compare these two nozzles and therefore, we define area ratio as exit area divided by the throat area.

The reason being I could have had a larger chamber something like this with much larger chamber, but still even for a larger chamber the throat area would be the same for a given condition namely V t is equal to A t over here, I think we must keep this in mind. Area ratio is always defined with respect to the throat that is exit area divided by the throat area.

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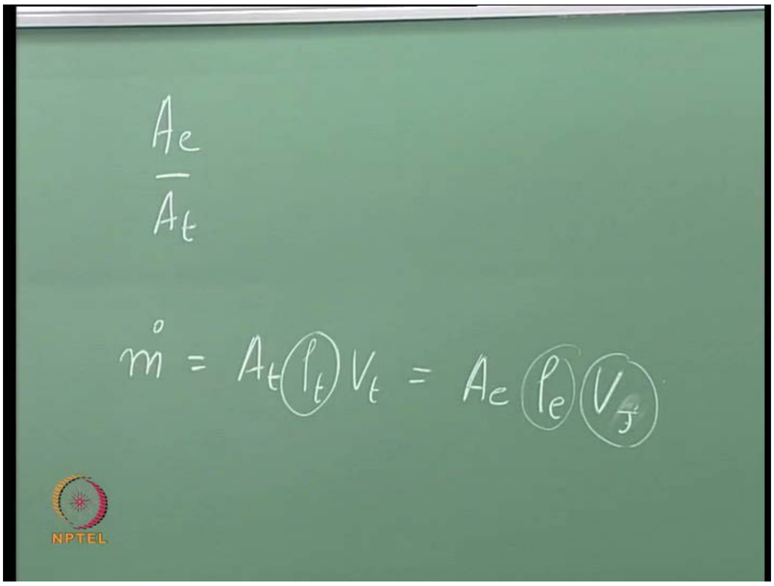

I want to determined, let us go ahead and try to write an expression. Therefore, I am interested in finding the value of A e by A t for nozzle and how do it. I just look at the continuity, I look at the mass which is coming over here, mass which is passing through the throat, mass which is passing through the exit and I write m dot is equal to the mass which is passing through throat rho t into the velocity at the throat is equal to the area at the exit rho at the exit V at the exit is it. If anybody has question please I think this the time to (( )).

Therefore, we find that I need the condition at the throat namely the rho t at the throat I need to be able to find out, I also need rho e, I know V e, V e is nothing but the velocity with which is it exiting this will be equal to the V J, which I have already derived. Therefore, I need to find the conditions at the throat. Therefore, let us first spend a couple of minutes on deriving the expression for the conditions at the throat, which are so critical to a nozzle.

Let me again repeat. The condition at the throat will specify the mass flow rate, because it is chocked over here I will come back this later, but let us first find out what are the density pressure and temperature at the throat.

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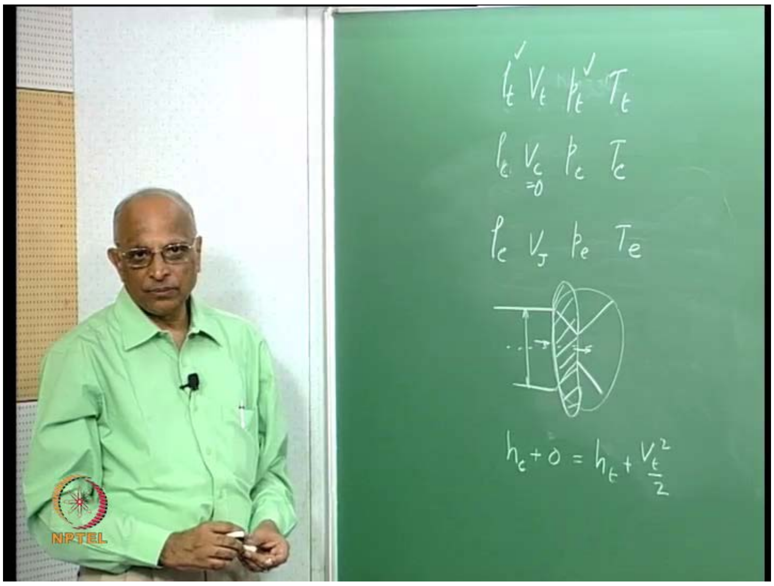

We see the throat is define by density at the throat rho t, V t, pressure at the throat is P t, temperature at the throat is T t, that means subscript t denotes the throat condition. And how did we define the pressure conditions or the chamber conditions rho C capital C over here velocity in the chamber, which we said was equal to 0 pressure at the chamber temperature in the chamber, at the exit rho exit V exit, which is equal to the jet velocity at the exit, P at the exit t at the exit; well these are the variables what we have.

I want us to find out the value of rho t as a function of rho c may be P t as a function of P c and T t as a function of T c. Therefore, we again just look at the conditions. We tell ourselves again, we are deriving the same expression we are interested in the condition at the throat over here, the conditions are given by subscript t over here for rho V t and all that, this is the chamber condition, we treat this as a control volume or rather now we are considering our attention is only in this small region, which I show hatched over here, gas enters at a pressure P c at velocity 0 at a temperature T c at the throat it leaves at a condition rho t at a velocity equal to the sound velocity, because its choked at a pressure P t and at a temperature T t.

For let us write the expression for this control volume. Let us again assume adiabatic condition and therefore we can write the enthalpy entering is h c plus kinetic energy 0 is equal to h at the throat plus, I have V t square divided by 2 kinetic energy. We must be able to write this is the steady flow energy equation same mass flow is there, enthalpy comes over here corresponding to this initial kinetic energy is 0 exit or at the throat the enthalpy is h t and V t square by 2 is the or V t is the velocity at the throat kinetic energy at the throat is V t square by 2.

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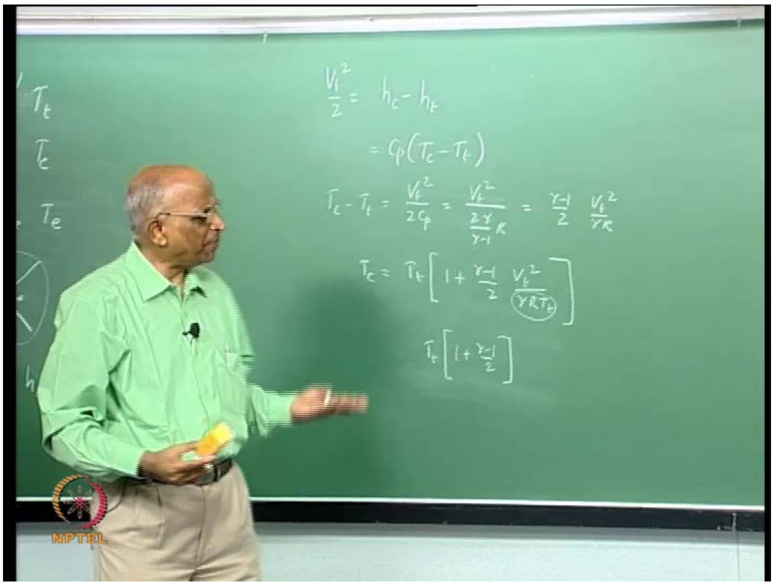

Now let us simplify this equation. We get from this equation V t square divided by 2 is equal to h c minus h t and what is the difference in enthalpy is equal to C p T c minus T t and therefore what is T c minus T c, T c minus T t is equal to V t square divided by 2 C p. Now please just if there is anything please let me know. What is the value of C p in terms of gamma V t square divided by 2 gamma divided by gamma minus 1 into R, how did this come we are derived in the earlier class C p minus C V is R C p by C V is gamma and therefore, C p is equal to gamma by gamma minus 1 into r and therefore, I can write this expression as equal to gamma minus 1 divided by 2 into V t square divided by what is it I get gamma R.

And therefore, I can now write the value of T c, I take T t on the other side is equal to T t into what I get now 1 plus gamma minus 1 divided by 2 into I. Now write V t square divide by gamma r into T t. What did I do, I have taken T t at the bottom and therefore, I have gamma minus 1 V t square by gamma R here is there some 2 missing no it is all right and now, I know gamma R t is the sound speed or gamma R into T t is a sound speed at the throat V t is also equal to the sound speed at the throat therefore, this is the mach number square and I get 1 plus gamma minus 1 by 2 into mach number square mach number is one and therefore I get the value of T t as equal to 1 plus gamma minus 1 divided by 2 or this gives me the value of the temperature at the throat as a function of the chamber temperature as equal to T t by T c is equal to now this becomes gamma plus 1 by 2, I take it the other side (( )) 2 plus gamma plus 1.

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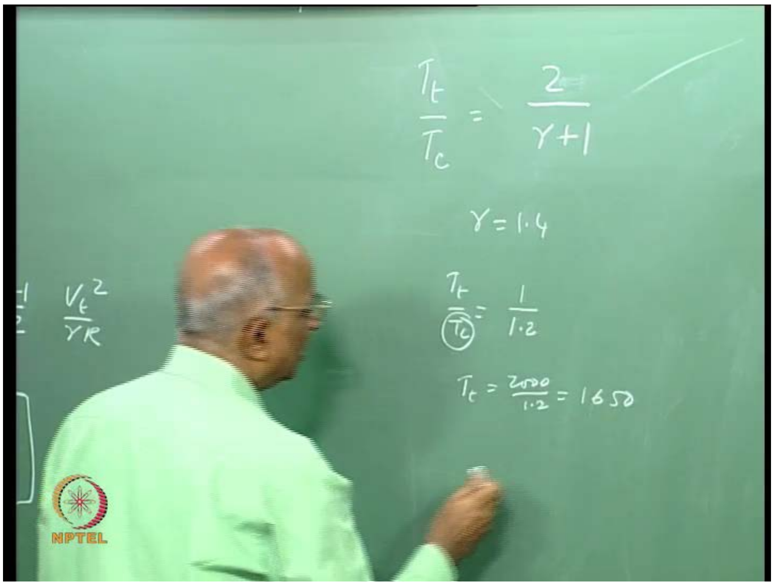

Therefore, what is it we find that the temperature at the throat is approximately 1 over 1.2 times that in the chamber or rather if the chamber temperature is something like 2000 then it will be something like 1300 or 1500 degrees centigrade; in other words, if gamma is equal to 1.4 the value of T t by T c is equal to 1 over 1.2 or depending on the temperature here if the chamber temperature is 2000 the value at throat is equal to 2000 divided by 1.2, which is equal to may be 180 may be something like 1600 and may be 50 or something like this. Therefore, the temperature falls at the throat and it is around depending on the value of gamma you get a smaller value.

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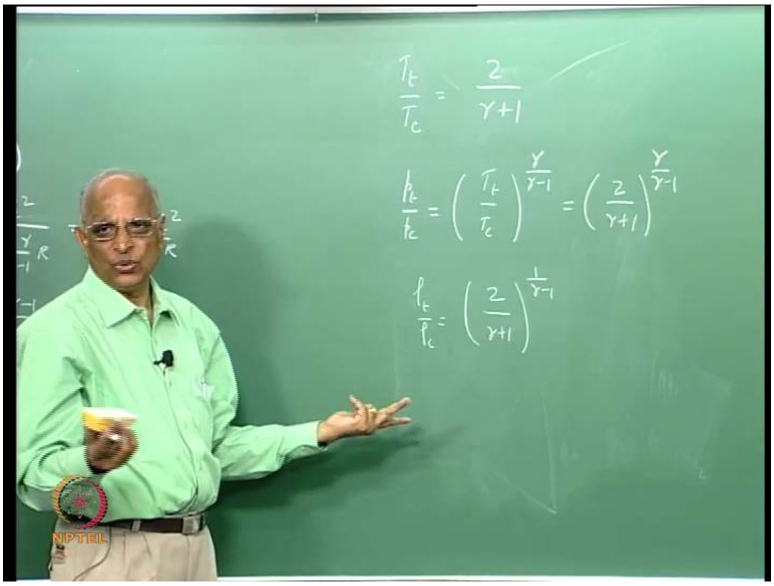

Now what will be the value of P t by P c, we have derived the expression in the last but one class, what did we tell it is equal to T t by T c to the power gamma by gamma minus 1 please look back let us take and how did we get this we had p by rho is equal to P by rho is a constant P by rho t is a constant solving for this we got this particular expressions. In fact, you will remember in the expression for V J what we had you remember we had the expression 1 minus P e by P c to the power gamma minus 1 by gamma how did it come, this was essentially T e by T c and when we converted it we converted it in terms of the pressure ratio

What is the value of rho t by rho c 1 over gamma this that is equal to 2 over gamma plus 1 to the power 1 over gamma minus 1 and this may be I should have written here as 2 over gamma plus 1 to the power gamma divided gamma minus 1.

What is it we have derived we derived the conditions at the throat namely the value of the temperature at the throat the value of pressure at the throat the value of density at the throat as a function of the conditions in the chamber pressure, which is known to us which is what we are given with may be the that is the chamber condition.

I want us to go back and apply these three relations over here we know the density at the throat may be I have to find out the density at the exit and find out the value of the exit area ratio as a function of the exit pressure or exit pressure as a function of area ration I am interested in.

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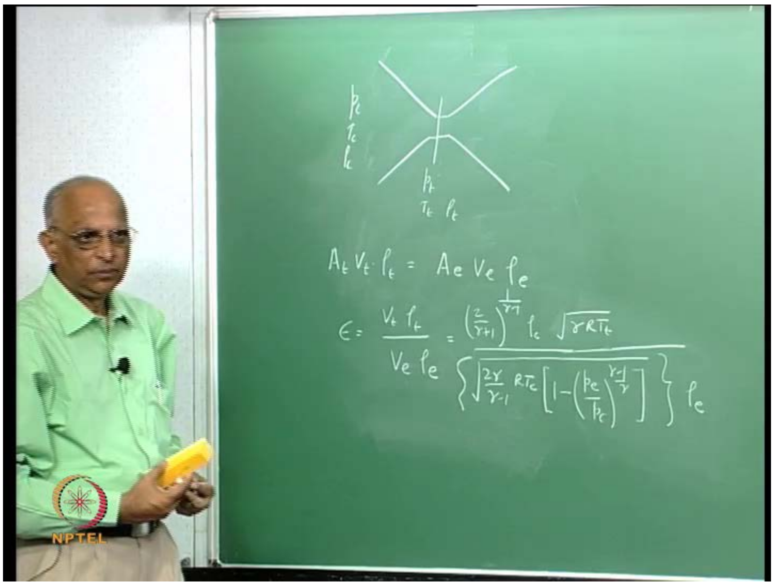

Therefore, I hope by now we know how to evaluate the conditions at the throat of a nozzle and all what we have learned so far is, if I have a throat coming from a chamber pressure P c temperature T c density T c I know how to find out the conditions of P t T t and rho t agreed.

Now, let us go back and solve that equation namely we said area at the throat velocity at the throat into the density at the throat is equal to area at the exit velocity at the exit rho at the exit or rather from this I get the area ratio A e by A t is equal to V t into rho t divided by V e into rho e.

I want to substitute the values, I know the value rho t in terms of rho c; therefore, I say this is equal to 2 over gamma plus 1 divided by 1 over gamma minus 1, I take this particular expression rho t by rho c is equal to 2 over gamma plus 1, 1 over gamma minus 1 and then I now have the value of rho t is now into rho c into V t, I still keep it as V t and now I know that V e is equal to V J what is the value of V J 2 gamma, gamma minus 1 R T c 2 gamma R T c gamma minus 1 into 1 minus P e by P c to the power gamma minus 1 by gamma under root into the value of rho e. Now, I want to somehow get rid of rho e also V t, V t I can write in terms of the sound speed and this is equal to A t and therefore here I can write it as equal to under root gamma R temperature in the throat.

Please be let us be very careful you know because these are all simple algebraic expressions we are substituting one into the other and in the process we are also learning how the properties are varying.

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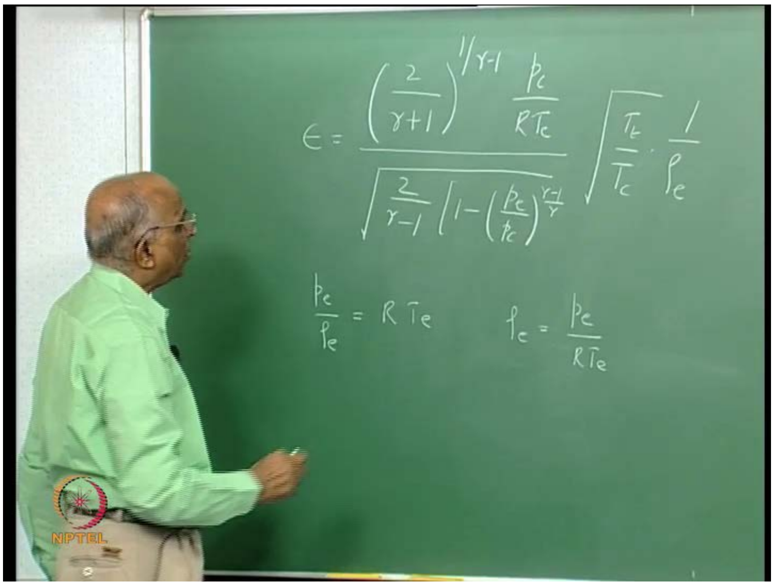

Let solve that equation for the; therefore, the area ratio epsilon is given by let us write it down 2 over gamma plus 1 to the power 1 over gamma minus 1 into rho c, rho c, I can write it as P c divided by R T c, P is equal to rho R T P by rho is equal to R p; therefore, rho is equal to P by R T made use of the ideal gas equation P is equal to rho R T and therefore rho is equal to P by R T P c by R T c.

And now, I have another value gamma r, now let us strike of some of the numbers here, here I have under root gamma under root gamma under root R under root R; therefore, now I get a value, which in the denominator would be two will keep will take P c outside 2 over gamma minus 1 into 1 minus P e by P c to the power gamma minus 1 by gamma under root. Now, I have under root T t here I have under root T c here is it T t c, 2 over gamma plus 1 P by R T c into under root T t on top gamma r get canceled; therefore, I had 2 by gamma minus 1 into this term T c over there.

I want to further simplify, you know we had derived an expression for area ratio as given by the above expression. We would like to simplify the expression by bringing by expressing as ratio of pressure as ratio of temperature, so that we can write it as a function of the P c and P e alone. For this purpose, let us take a look at what we can write rho e as maybe I can write the value of rho e in terms of the pressure at the exit, I saying pressure at the exit divided by rho e is equal to P V e is equal to R into T e. Therefore, that is pressure divided by density is equal to specific gas constant into the temperature at the exit. I simplify this expression to give me rho e as equal to P e divided by R T e. Therefore, now I can substitute the value of rho e as P e divided by R T e, so that now I get an expression for P c by P e this is one. Second is, I can also make some changes for the value of T t that is the temperature at the throat.

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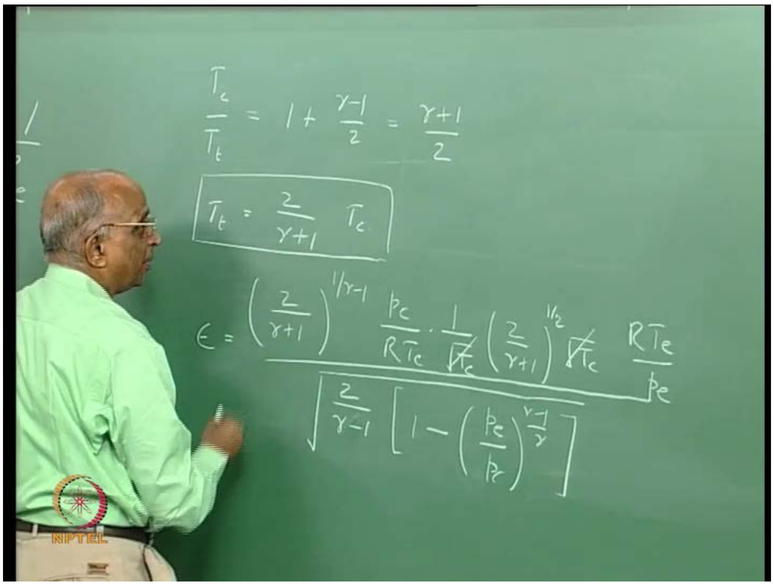

And we had seen earlier that the temperature at the throat divided by the temperature at the chamber at the throat the mach number is unity and therefore this is equal to 1 plus gamma minus 1 by 2 into 1 square or this is equal to gamma plus 1 divided by 2.

Well, you know there is some problem here the temperature at the throat reduces with respect to the chamber the chamber is stagnation; therefore, this expression should really have been something like T c that is the temperature in the chamber divided by the temperature at the throat. Therefore, now I can write the temperature at the throat is equal to 2 over gamma plus 1 into the temperature of the chamber.

Now, these two things namely the value of temperature at the throat in terms of the chamber temperature and the exit gas density in terms of P e by R T, I substitute in this particular expression and now we therefore get the area ratio epsilon as equal to 2 over the same things I write again gamma plus 1 divided by 1 over gamma minus 1 and now P c divided by R T c and now I get the value of T t divided by T c but my value of T c is therefore, I write it as 1 over under root T c, which is over here under root T t, I can write as 2 over gamma plus 1 divided by half into under root T c this is where I have written this and 1 over rho e is equal to R T e by P e and this is divided by the same value what I had here namely 2 over gamma plus 1 under root 2 over gamma plus 1 gamma minus 1 into 1 minus P by P c to the power gamma minus 1 by gamma close bracket over here, here also the bracket should have been closed here. Now, let us simplify this you find that you have under root T c under root T c cancels and now if I were to put it in terms of T by T c in terms of P c by P e

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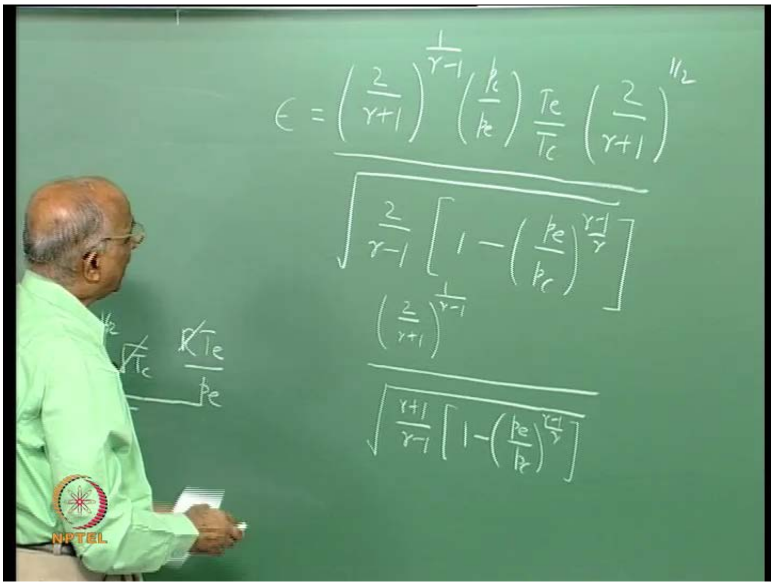

I will get an expression which gives me epsilon is equal to or the area ratio is equal to 2 over gamma plus 1 divided by 1 over gamma minus 1 to the power, now I have P c here I have P e here let us write it has P c by P e and now if I take R also cancels over here; therefore, now I have write T e is left over here that is the exit temperature and there is nothing else here let us write that down I have the value of t e over here and I have taken P e inside and here I have T c over here and this divided by of course, I need to take 2 over gamma plus 1 this is 2 over gamma minus gamma plus 1, 1 over gamma minus 1 and this I take 2 over gamma plus 1 half into under root of the same denominator, which comes over here 2 over gamma minus 1 into 1 minus P by P c to the power gamma minus 1 by gamma and close bracket here.

Now immediately I see that 2 over gamma plus 1 2 and gets cancel over here gamma plus 1 comes on top and therefore now I can write the denominator as equal to gamma plus 1 divided by gamma minus 1 into 1 minus P e by P c to the power gamma minus 1 by gamma close bracket over here and now let us simplify the numerator, I get 2 over gamma plus 1 divided by 1 over gamma minus 1.

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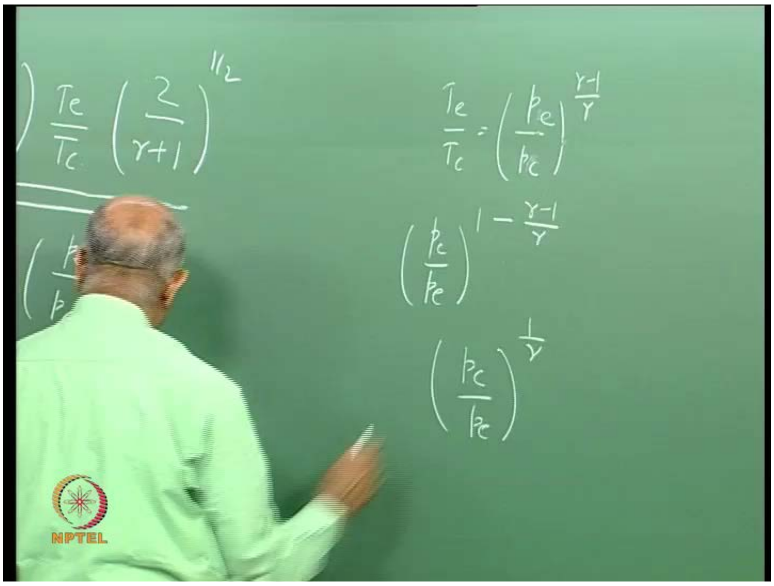

And now can I express these things together, can I express T e by T c in terms of P c by P e see we have been doing this we always set T e by T c using the isentropic expansion we can always write it as T e divided by T c is equal to P c divide by P e to the power gamma minus 1 by gamma you will recall we have done this several times and therefore, if now I say P c by P e and I add this together I will get an expression in terms of let us put it P c by P e and now I have the value over here P c by P e and now I have T e by T c T e by T c it should go as P e mind you in the same order P e by P c and therefore, I will get P c by P e into the value of 1 minus gamma minus 1 divided by gamma, which is equal to P c by P e to the power 1 over gamma because 1 minus 1 plus 1 over gamma it becomes 1 over gamma.

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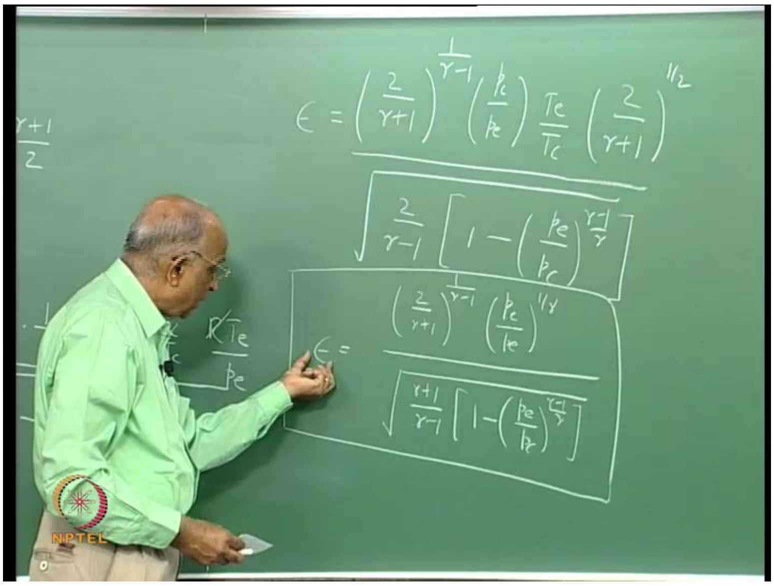

And therefore, I can write this as equal to P c by P e to the power one over gamma and therefore, my net expression now becomes 2 over gamma plus 1 to the power 1 over gamma minus 1 P c by P e to the power 1 over gamma divided by gamma plus 1 divided by gamma minus 1 into 1 minus P e by P c gamma minus 1.

What does this expression tell us, this expression tells us that the area ratio of a nozzle can be given by this particular expression and as the chamber pressure increases the area ratio increases or rather as the ratio of P c by P e increases the area ratio increases, which can come about either by increasing the chamber pressure or by decreasing the exit pressure. If I have a very low value of exit pressure my pressure ratio is larger and I require a larger area ratio nozzle; of course, gamma also plays a role, but a secondary role, but the main aspect of area ratio comes from the change from the variations in the value of the chamber pressure to the exit pressure.

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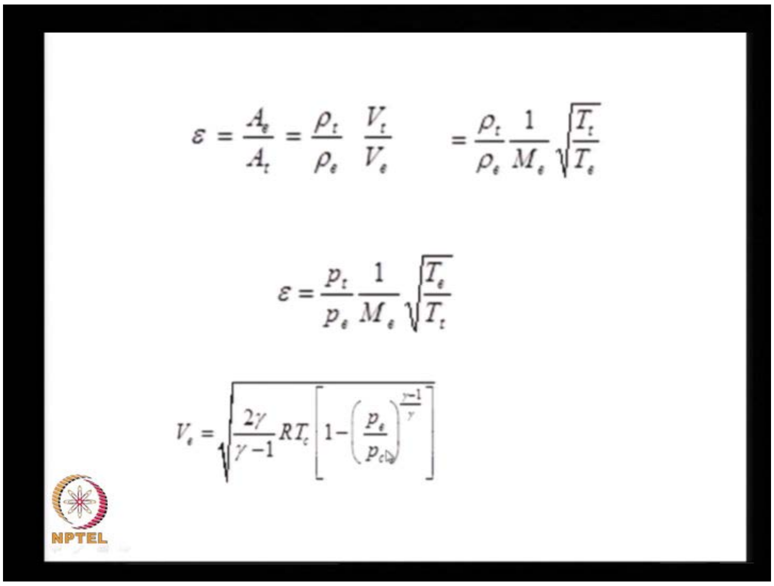

Let us take a look at some of the values maybe, which I have plotted in the slides over here. See I quickly run through whatever is given here area ratio is defined by the value of A e by A t and this is the expression we had got we had the jet velocity V e given by 2 gamma minus 1 gamma minus 1 r T c one minus P e by P c.

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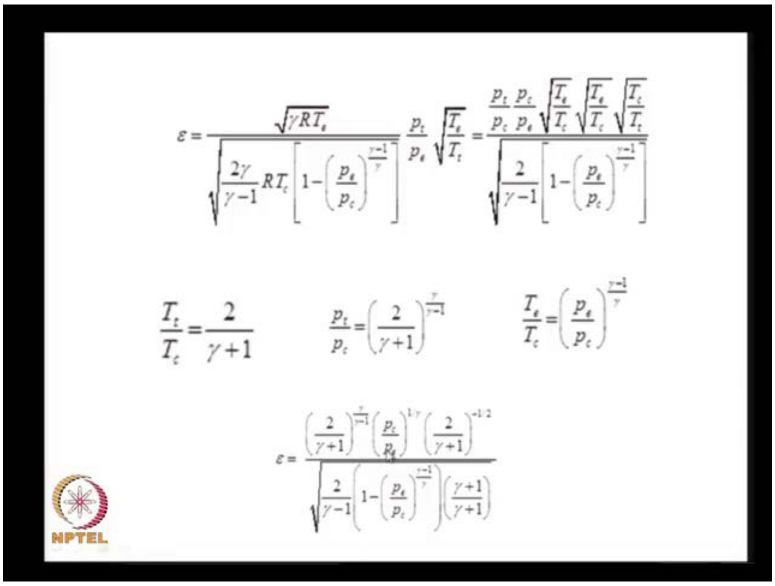

And thereafter we wrote the area ratio in terms of these parameters and got this particular value which worked out to be 2 over gamma plus 1, 1 over gamma minus 1 P c by P e 1 over gamma..

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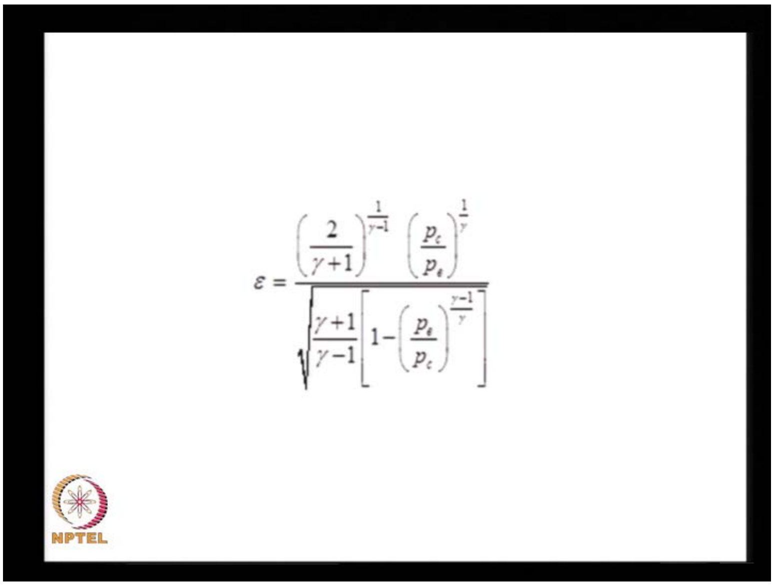

We should have add gamma, I think we have solved 1 over gamma 1 somewhere. We should have got the expression as gamma plus 1 into 1 minus P e by P c, please check it somewhere you would have left out something and when I plot this number.

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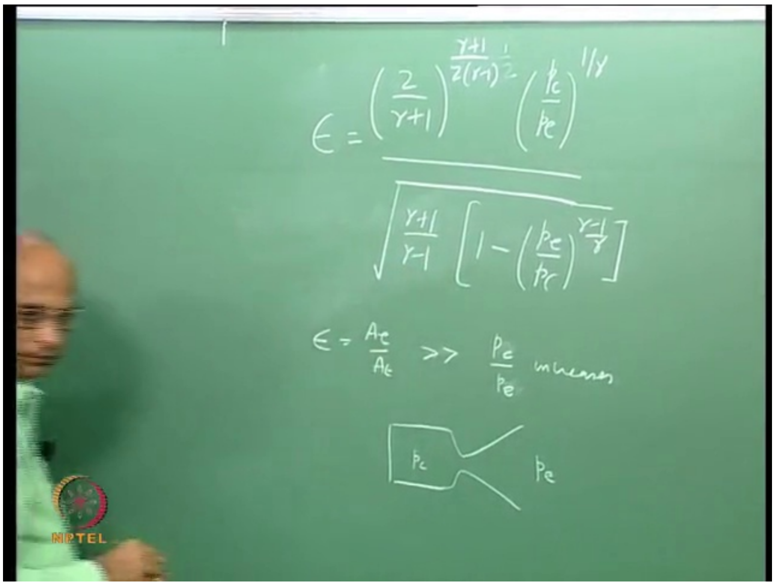

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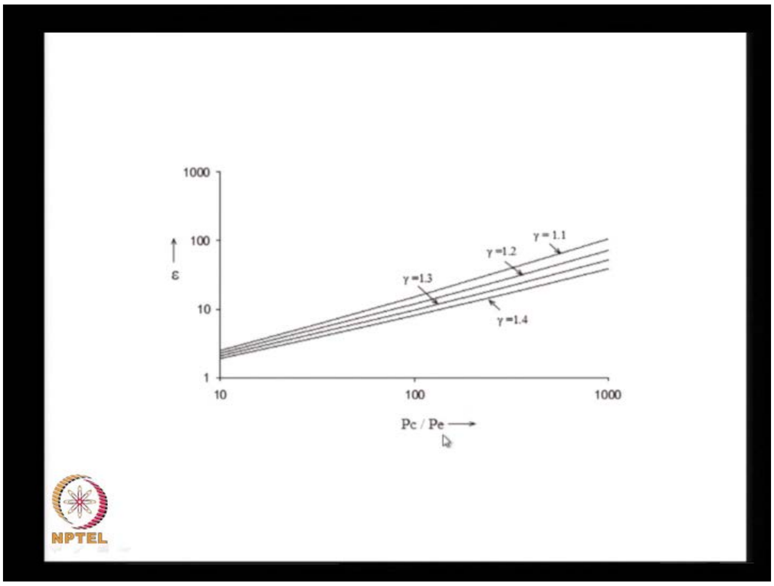

I get the area ratio as a function of P c by P e as P c by P e increases the area ratio increases and in fact as the gamma decreases from gamma of 1.4 to 1.1, I find a larger area ratio is required to give me the same value of P c by P e.

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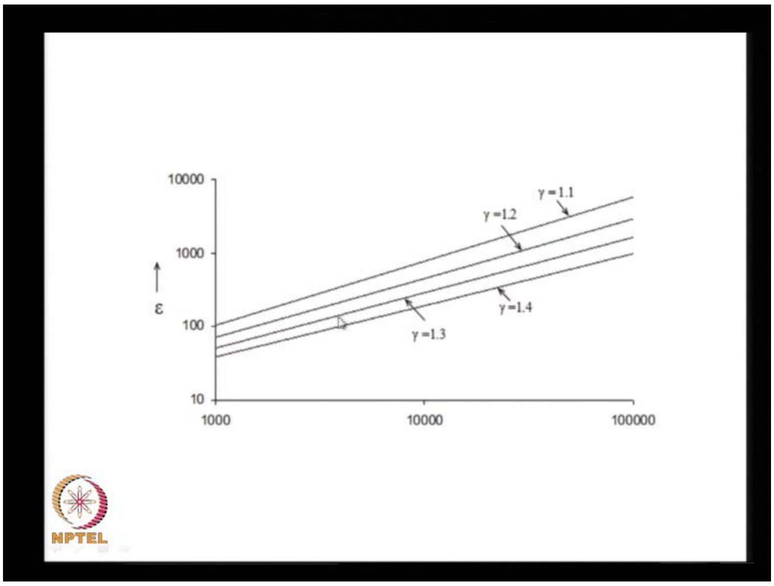

I put it for larger value of pressure ratio here again the value is P c by P e as a function of the area ratio, you find that as gamma decreases I need a larger value of the area ratio. In other words what it tells me is if my gasses have a smaller value of gamma then I need a larger area ratio to give me the same value of pressure ratio. I think this is all about area ratio.

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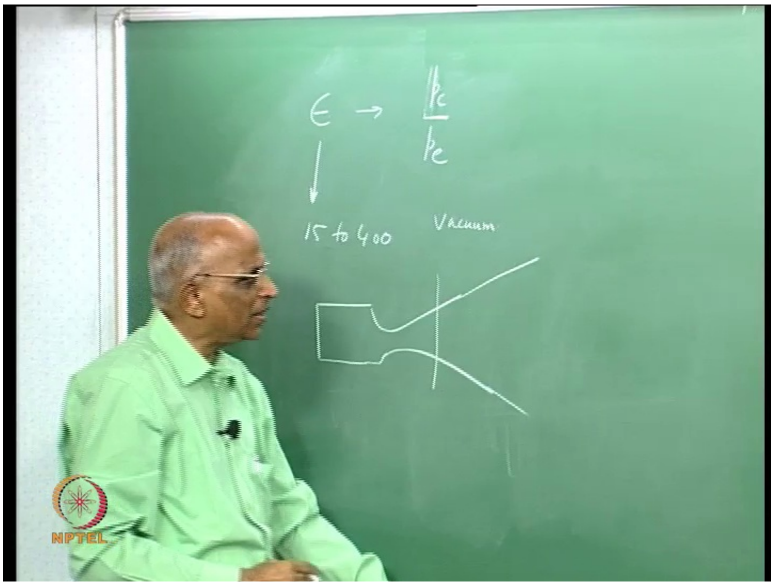

You know, what is it we have done so far; we found out the value of the area ratio and related it to the value of the chamber pressure divided by the exit pressure over here p e. Now in general area ratio of most of the nozzles will be between let us say 15 to 400 this is the type of area ratios what we employee.

If we were to look at the expression for area ratio you find that when P becomes zero, I need area ratio, which is something like infinity, I cannot have infinity, because I cannot offered to have a rocket motor, which gives me a very large value, I cannot keep on extending because the mass of my rocket will keep on increasing; therefore, the general practice is to have area ratios between 50 15 and 400, 15 for those rockets, which operate within the atmosphere or within near to the earth and 400 or values around this for rockets, which operate in the vacuum regions. Therefore, the question which now comes is, if I give a supposing I have a rocket nozzle let us have some clarity on what I propose to do now.

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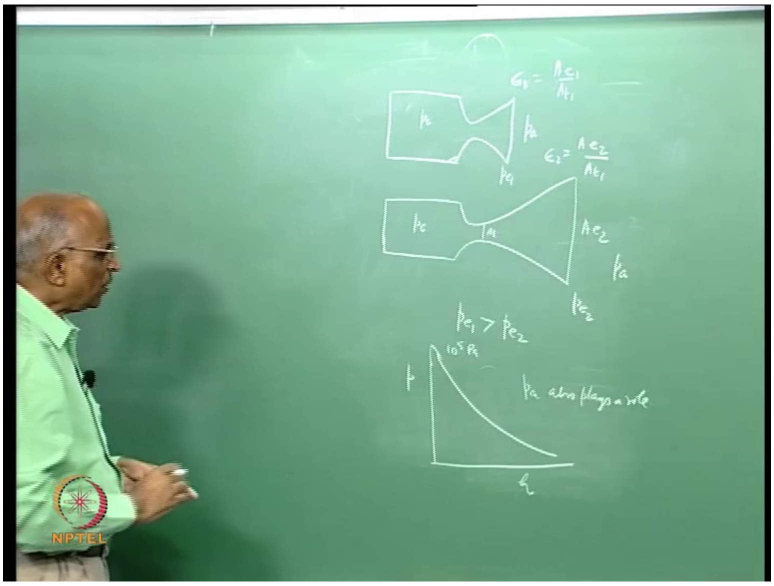

Suppose, I have a rocket nozzle, which let us say has a small value of A e by A t, this is the value, I say epsilon 1 which is equal to A e 1 divided by A t 1. For the same condition of the throat, I also have another rocket, which has a larger area ratio, let us say A e 2 for the same value of let us say A t 1; that means I have epsilon 2 is equal to A e 2 divided by A t 1. Now the thing what I want to describe is suppose the chamber pressure is the same in both the cases, what I am going to get here is a smaller value of P e 2 and here I get t 1 or rather I get the value of p 1 will be greater than P e 2. I have a smaller nozzle it expands to a higher value of pressure; I expand it still further; therefore. the value of P e 2 is less than P e 1.

Now, if we have rockets of different area ratios and we also know may be I plot the value of pressure as a function of altitude pressure keep decreasing as altitude increases at ground level I have a pressure of let say one atmosphere of 10 to the power 5 pascal as I keep increasing altitude it decreases till the time we leave the atmosphere let say around 50 or 40 kilometers the pressure as gone down to a very small value and when I go to geosynchronous altitudes its almost perfect vacuum. Therefore, the ambient pressure also plays a role. Let us assume that in this case P 1 is there, I have the ambient pressure is P a over here the same ambient pressure is over here.

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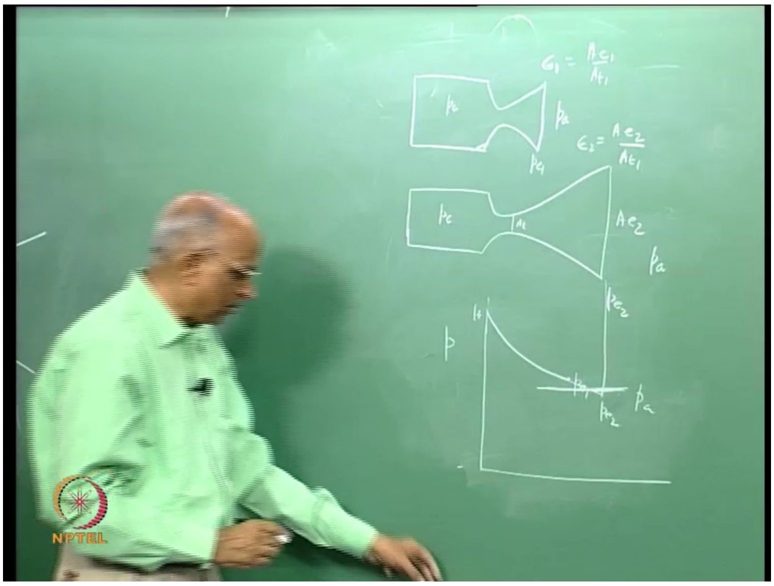

Therefore, let me plot it a little on a plot now. All what I am trying to do is, I am trying to plot the pressure and the pressure variation along the nozzle in the first case it starts with the value of P c comes down to a value of P e 1. In the second case, the same chamber pressure this is P c, this is the start of the nozzle and in the second case is it starts from P c, but continues further till I get a much lower value of let us say P e 2 over here. Now supposing, I consider a situation where in the ambient pressure is somewhere over here.

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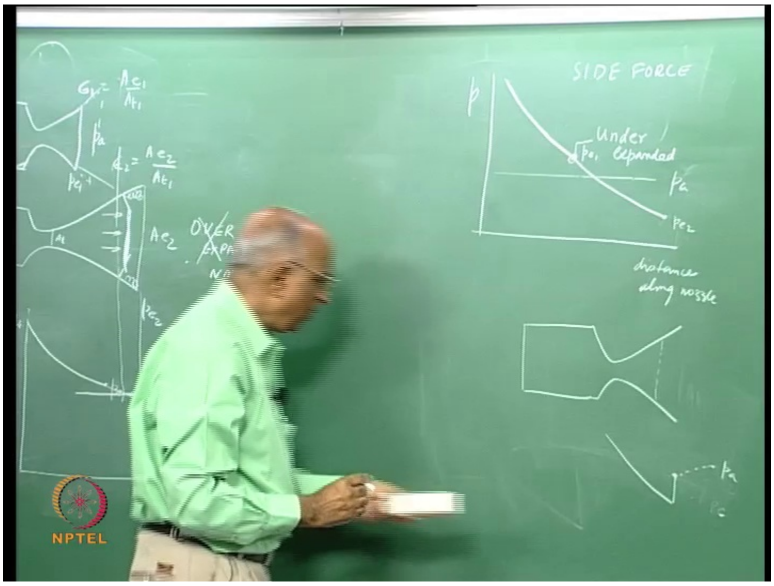

Let me re-plot this. What I am trying to tell you is the pressure is varying along the nozzle supposing the ambient pressure distance along the nozzle and this is the ambient value of pressure P a which is the value of the ambient pressure and now in the first case the rocket nozzle is smaller it comes over here. In the second case, the rocket nozzle is bigger and therefore maybe I expand it still further it comes over here, the first case is P e 1 the second case is P e 2.

Therefore in the first case, what is going to happen the pressure at the exit is greater than the ambient pressure. In the second case, the pressure at the exit that is P e 2 is less than the ambient pressure and this is what this graph tells you pressure at the exit for the first nozzle, which is small is higher than the ambient pressure, pressure at the exit is less than p a. Therefore, what is that I have done in the first case the expansion is not completed; therefore, I call this nozzle as under expanded nozzle it is not. In the second case, I expand it over and above the ambient pressure; therefore, I call this particular nozzle as over expanded nozzle.

Are there any defects in this? What I have done when the nozzle is small the expansion is less, what happens I am not able to get a high jet velocity because my exit pressure has still not been able to match my the ambient value that means I could have got much more had I really expand it a little bit more come over here or rather it would have been good for me had I expanded the nozzle something like here till the time the pressure matched over here.

What is the problem with over expanded nozzle? Well the pressure here itself is equal to the ambient pressure, the ambient pressure is now that means the pressure is going to decrease and if it is going to decrease it just not possible mind you the flow here is supersonic, it does not know the conditions what is existing over here all of a sudden the supersonic flow finds a higher pressure because it has already been expanded to a lower pressure and therefore, it is necessary that something like a shock stands over here; that means, I have supersonic flow it is not able to see anything before it, but all of sudden when the flow reaches it sees a higher pressure and therefore something like a shock is required to match the exit pressure and what could happen let us plotted it now. What is going to happen, I have something like this I have a nozzle here and now the pressure has come to the ambient over here and therefore, if I were to plot the pressure, the pressure is going to decrease I should have a shockwave and the flow downs stream of the shockwave is sonic and therefore it will take me back to the ambient pressure; that means there is going to be a shock which shock the flow is going to separate out. If it is going to separate out (( )) region of higher pressure, and since I have a higher pressure here, the performance of this nozzle may be even better had flow not separated. But, normally this flow separation does never happen symmetrically, and it’s leads to something like side forces, and therefore over expansion is not preferred at all. I will get back to this point; this point will not be clear at this point in time.

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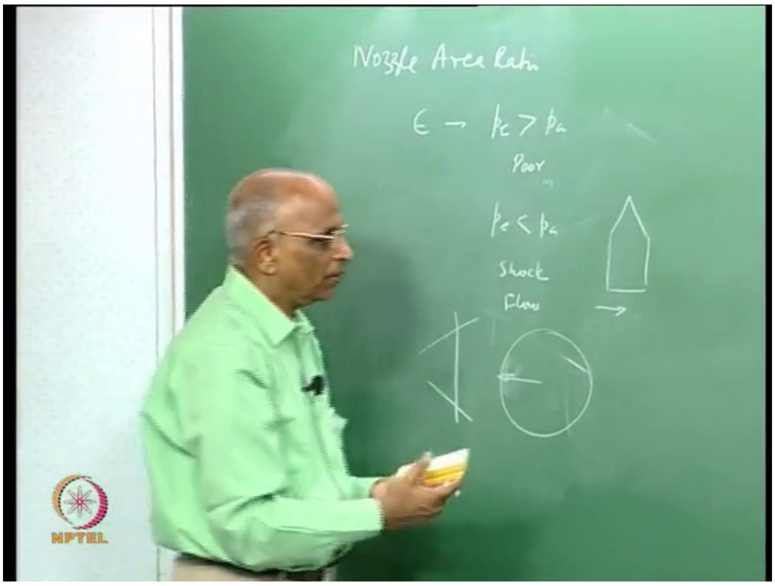

All what I am trying to say is, well, if my nozzle area ratio epsilon is not properly tailored and I get p which is greater than p a. I have under expanded nozzle, in which case my nozzle performance is poor; I do not get the high value of p a. But, incase my p e is less than p a, I will have something like a shock; I have something like a flow separation taking place in the nozzle. And if I consider a section of the nozzle, that means I have this; I consider someone over here flow separation taking place. Flow separation doesn’t takes place uniformly, with result at some place, I have higher pressure, where flow separation takes place somewhere flow is not separating. Low pressure and therefore high pressure which give me a higher force and the rocket in that case will see something like a side force, because of the higher pressure in the nozzle and this is again non desirable.

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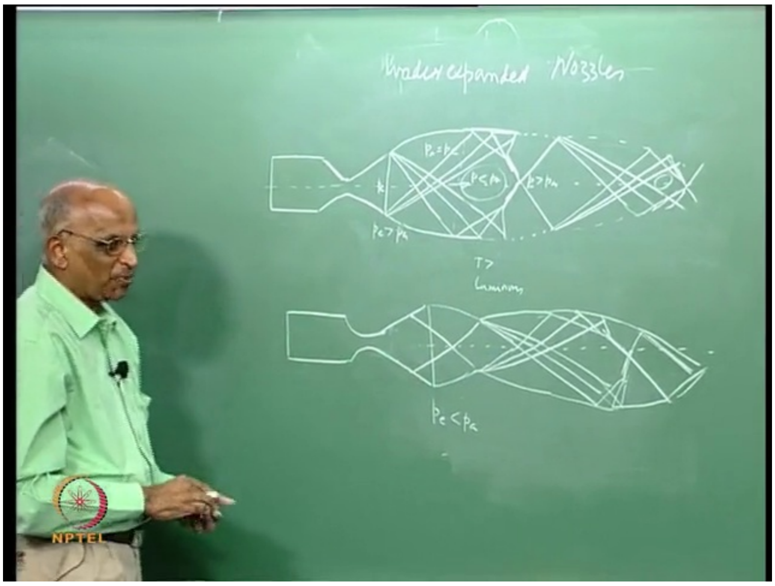

We will come back to this, but after seeing a few, few pictures on flow separation in nozzles. What do we really mean? Let us go back and ask ourselves, can I make a plot of flow separation or let us say an under expanded nozzle. How does the flow takes place? Let us consider this diagram. A chamber, a nozzle, now what is it we are telling this is centre line. We tell ourselves for the under expanded nozzle p e is greater than p a. Therefore the flow comes here, it meets lower pressure; therefore I have something like flow is going to expand out like this. And how does the flow expand out, I have a rare fraction fans which are generated, (( )) expansion at a point. And similarly over here that means the plume comes here, this is the low-pressure region; this is higher value of pressure and when the flow expanse out I have here the back pressure, which is the ambient pressure is equal to p e. And then the flow these are the expansion waves which are coming over here. Similarly over here again on the other side, I have the same expansion fans coming over here.

Why do we need these things, because at this centre the flow velocity is still higher. Therefore, what is happening? Here the pressure has been matched, but here I have expansion, therefore here the pressure is going to be less than the value of p a; that is the nozzle, that is the flow pressure here is going to be less than p a. And then the rare fraction fans, touches the boundary of the plume, you get compression waves coming like this, and they form a compression wave like this. Similarly, I get all these things forming compression waves and the net compression waves coming over here; I have compression region over here. And therefore now, because of compression my pressure becomes greater than the ambient pressure. But on the outside, the effect of this is still give me there, same value and these compression waves travels still forward; it is the boundary of the plume.

And when how compression waves or a oblique waves strike an interface, I start generating rare fraction fans again, that means I start generating rare fraction fans again; over here it strikes, I start generating rare fraction fans again. And then this comes on strikes here, I again get an oblique shock waves; I again strikes the plume over here; I again get oblique or shock waves and this is my shock waves at this types of things continues. In other words, I have something like a expansion fan, I have a region of low pressure, then I have oblique shock waves and these oblique shock waves give me higher pressure. Again I have smaller region and again high pressure region and this continues. In other words, I have regions wherein pressure is higher pressure is higher and the whenever pressure is higher the temperature is higher. If the temperature is higher, the flame becomes (( )) of more luminous, when temperature is higher you can see something, because it becomes more luminous.

We find that because of under expansion, there is further sudden expansion that means there is an expansion fans and this expansion fans impinges on the plume surfaces. And when the expansion fans impinge on the plume surface, the expansion is reflected as a compression that means as weak oblique shocks. These oblique shocks further compress the medium. The interaction of the compression waves with the plume surface forms expansion waves and the process of compression and expansion continues.

If I have an over expanded case, and let us put that down also such that the we understand the wave pattern, little bigger nozzle. Now I have p e which is less than p a. What is going to happen, much earlier. I am going to get a shock which is going to make the pressure over here higher, because supersonic flow I need a shock which will match the higher value of pressure. Therefore, what is going to happen is the boundary will come down like this; I have a shock waves, it interacts with the boundary. And what happens is, when it interact with the boundary, I get expansion fans being thrown off and the plumes expanse over here. And similarly over here, let us plot the centre line again. You are getting, it’s thrown of over here; thrown of here, thrown of here, this continues over here. These again, the rare fraction fans interacting with the boundary forms an oblique shock. Similarly over here, they forms something like an oblique shock over here. And then these oblique shock interact with the boundary here, again you have rare fraction fans and the process continues.

In other words, in one case, I get a higher-pressure region little bit away from the nozzle exist. In other case, I get a high-pressure region just at the nozzle exist, that means over here, I get a high-pressure region, because I have oblique shock waves which create a higher-pressure region and I get a wave pattern something like this.

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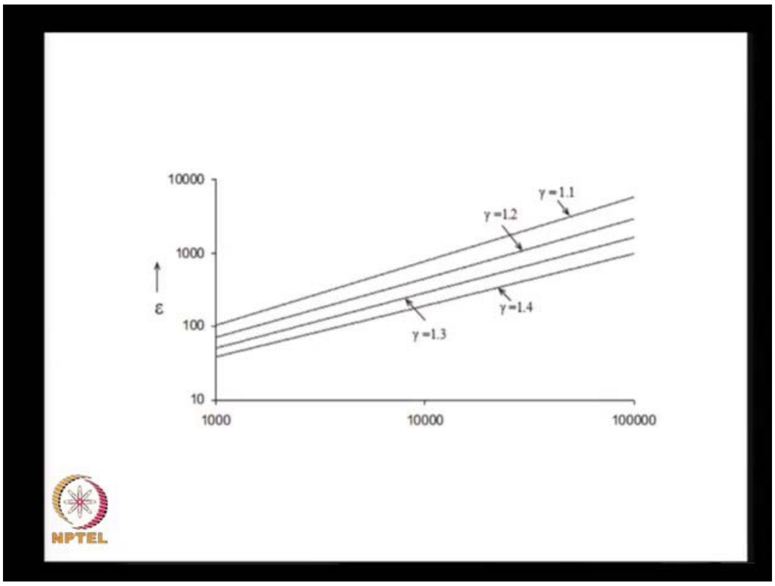

To be able to appreciate this point, I just took some pictures, which are some of the nozzle and this will become clear to you now.

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See this shows a particular second stage of PSLV, and here you see this is the divergence portion of the nozzle, which is chronicle nozzle. This is the compression chamber. And if I take the inside configuration of the nozzle, it will have a throat and will come back like this to the chamber. Therefore, I am looking at the outer portion of the nozzle here.

When the nozzle falls for some time, the nozzle become red hot mainly we are looking at this part. It becomes at red hot, because it hot gases. And then hot gases are (( )), this is something like a over expanded nozzle. You see the wide flame or plume over here. You find something like this oblique shock which stands over here and downstream is not clear, because they spray water and struck like that.

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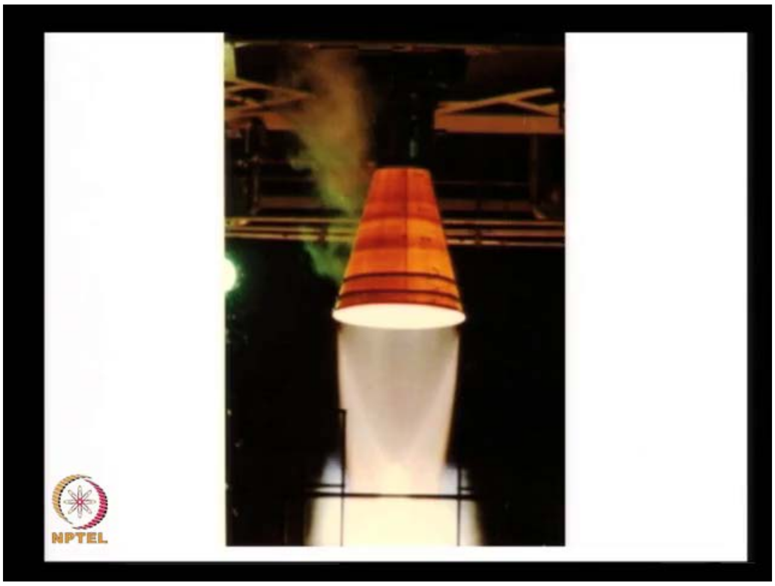

Let me go to the next one, I will show this again, the chronicle nozzle, it’s shown by the red color, because it is white; it is hot. The white part is the hot gases, which are going out. You find that there is something like an oblique shock over here, it interact along the base and subsequently some events are going to happen.

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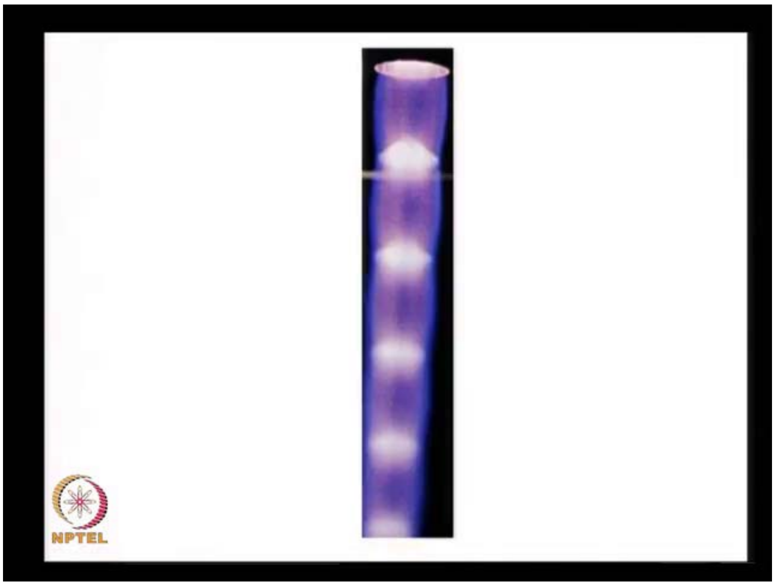

Let us go to some other experimental firing, in this shows the engine test wherein this is the exit of the nozzle, and in this particular case, exit of the nozzle is such that the flow is probably over expanded. And therefore, you have something like a shock waves which are coming. And what happens is the high pressure region over here, gives you a higher pressure and higher temperature if I have oblique shocks like this, which give me a high temperature region. It looks like a shock diamond you know, I have a high pressure region which is luminous. Afterwards, the oblique shocks comes here, I have rare fractions fans coming another oblique shocks coming; I have another white patch over here. Again the process, I have something like a series of shock diamond switcher coming. This is because at some places the flame is more luminous.

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I just continue with this, it shows SR-71 which is the plane. I see the shock diamonds over here, in this particular case. And we continue with this, this is a test of an engine. And here you find, there is a shock here and something like this. This is because the exit condition is either under expanded or over expanded.

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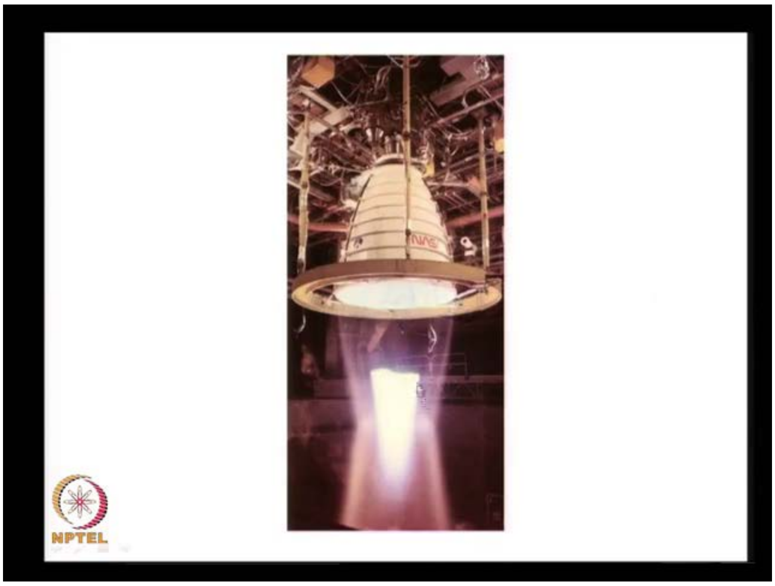

We will continue with this in the next class, I will just review this again and we will continue with what are the other things we have to do in the nozzle. Thank you.