Rocket Propulsion
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Lecture No. # 28
Feed Systems for Liquid Propellant Rockets

Well, good morning. I think today, we will start with this new chapter on a liquid propellant rockets.

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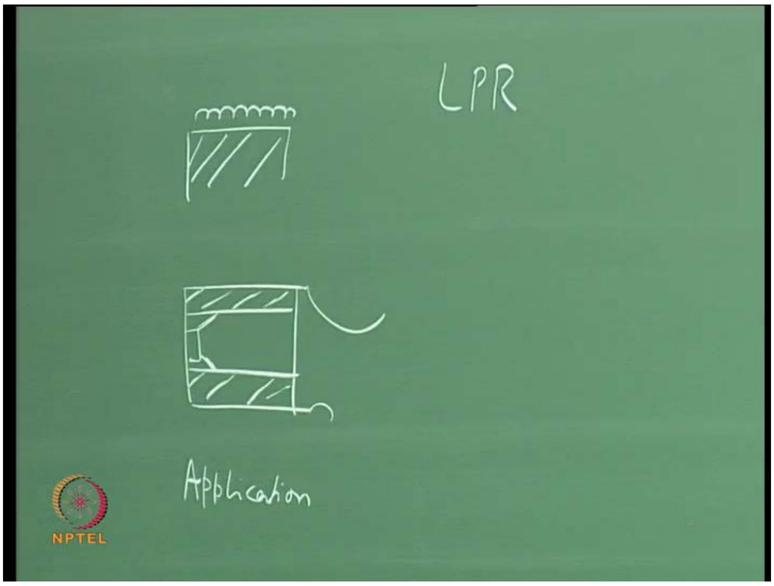

You know when we discussed solid propellant rockets, we told ourselves well. You have a solid propellant which burns you have a flame near to the surface. And once a solid propellant rocket begins to burn, it is impossible to extinguish. It this is what we told, because you have the grain in a in a case and once you ignite it, maybe you ignite the grain which is the grain over here, there is no way you can quench it, it continues to burn. Of course, there are some works which are done to see under what conditions you can stop the burning. And by rapid depressurization you can quench it, but this have not reached the question of being applied may be it is not reached a stage of application. Therefore, we say a solid propellant rocket once it gets started, you cannot control it, it burns and burns, that is about it. Whereas, when we talk of a liquid propellant rocket, we have considered the liquid propellant rockets you have considered different propellants. After all I inject a propellant into it, I can always control it and therefore, there are certain advantages which are liquid propellant rocket will have.

Let us examine these things, but to get started with this liquid propellant rockets, I thought let us go ahead and look a nature and we did examine when we considered the question of theory of rocket propulsion.

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We talk of a small insect known as the bombardier beetle, you will recall. What did we tell ourselves at that time? This particular insect is something you know which is smallish may be a centimeter to 2 centimeters also. And it is somewhat heavy and we find it all the time at all places, it sort of unveiled it cannot fly that rapidly. And therefore, it is always attacked by insects and also it is harmless, it does not bite, it cannot fly much. We just pick it up on a piece of paper and throw it put, whenever it comes. This particular one knows as bombardier beetle, some articles have come out on it in the last 10 to 15 years. And one such article came in the proceedings of the U S national academy of sciences in 1997, it is volume 94. It runs over 5 pages from 1692 to 1697. You know the beauty of this is we must be familiar with what happens around us.

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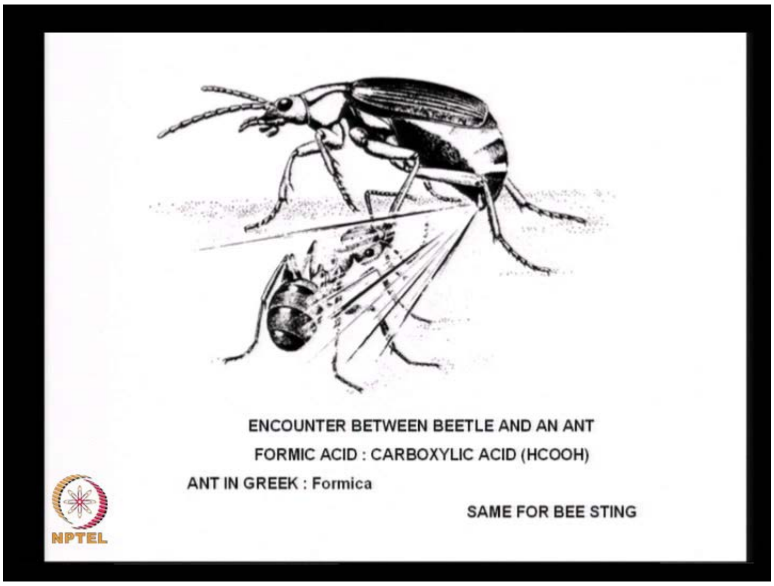

And this one as I was telling you this particular bombardier beetle is attacked by ants, and what does ant do? It stings us. Why do feel a sting? It injects some formic acid into our system. Formic acid is something like carboxylic acid and that is why you feel a sting and that is the same sting which when a bee also stings us we feel pain because something is injected into us.

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In fact, the ant in Greek is known as Formica because it bites us and injects the formic acid into us, and this same ant also pesters this beetle by stinging it. And what mechanism does this beetle have to escape from it or to get rid of the ant? What it has is, it has one chamber in it is stomach wherein, it produces hydrogen peroxide. In the other chamber, it produces a fuel like hydroquinone which is hydrocarbon. And whenever something attacks it flexes, it is muscles and pushes the hydrogen peroxide and hydroquinone into a third chamber, this third chamber is coated with some enzyme, which is catalyst.

Enzyme is something you know like even when we make the battle for making idly or something you know we put some yeast into it and it foams and all that so, also you have this enzyme coated third chamber, wherein the 2 things mixed together. And in the presence of the catalyst, the hydrogen peroxide and the hydroquinone they react and form hot gases and it squirts it, squirts it on the ant and therefore, the ant gets driven away. And this is nature's way of protecting this. It is a very unique way of evolution of species. All the species if you look at Darwin's and all that, it has come through some hierarchy, but this seems this particular insect seems to be different from the other species, but it is very illustrative of something which I will now tell you.

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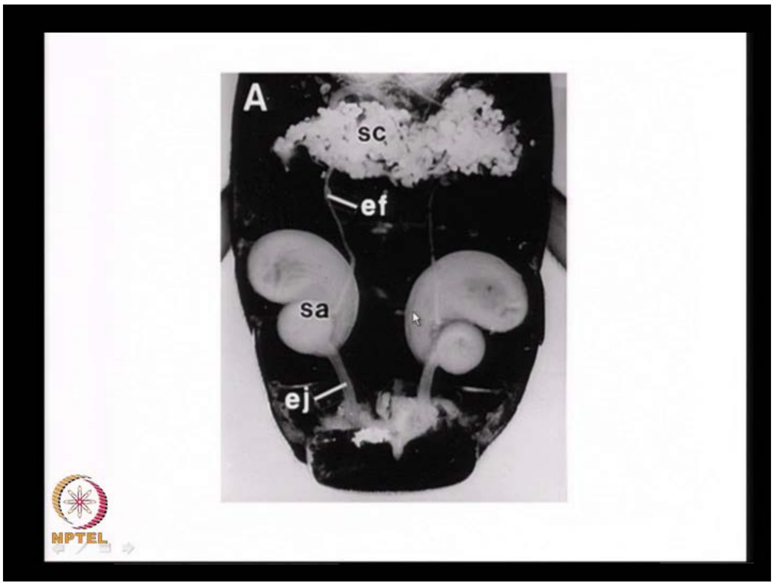

Let us go ahead and see what really happens. In one stomach; you create H 2 O 2, hydrogen peroxide. In the other chamber, you create hydroquinone which is the fuel. Then it wants to squirt hot gases out of it, it pushes this hydroquinone it pushes this hydrogen peroxide into this third chamber which is coated with enzyme, and it reacts, chemically reacts to form hot gases which it squirts out.

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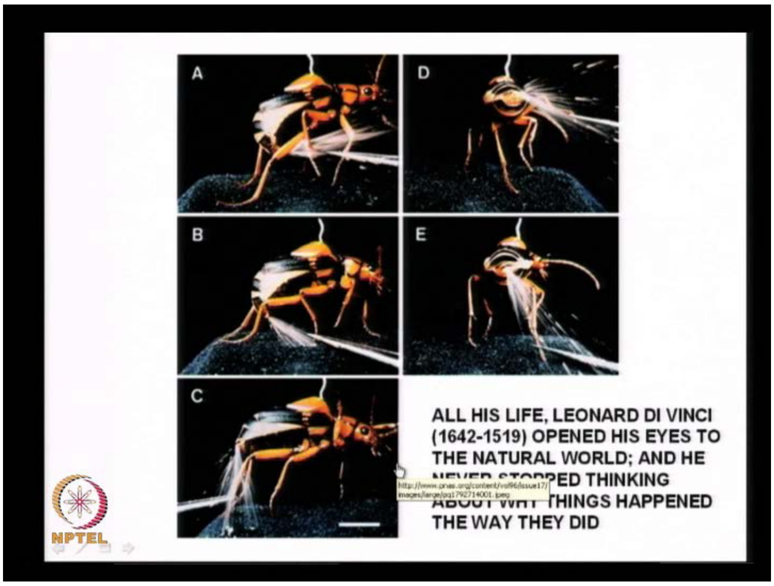

Well, the experiments which I told you at the national academy of science is one (( )) and others have been doing a number of experiments. They take something like a fork here, and they try to place it mimicking the ant and immediately it squirts out the hot gases. They put this particular intrusion over here, mimicking the ant and it pushes the gas. Therefore, it is able to squirt the hot gases in the different directions. You put this over here and it squirts out the hot gases in this direction and so on.

You know I was reminded of this Leonardo Di Vinci. You know he was the painter, who lived in the late sixteen century. And you know he made everything, he sort of looked at the birds flying, he tried to construct an aero plane, he made bridges of course, he was a famous painter, you will remember Mona Lisa painting. And all in his life you know I think we should remember this, he opened his eyes to the natural world and he never stopped thinking about why things happened the way they did. And so also may be if we had seen this insect long back, maybe we would have seen, we can have something like an oxidizer may be fuel injected into a chamber.

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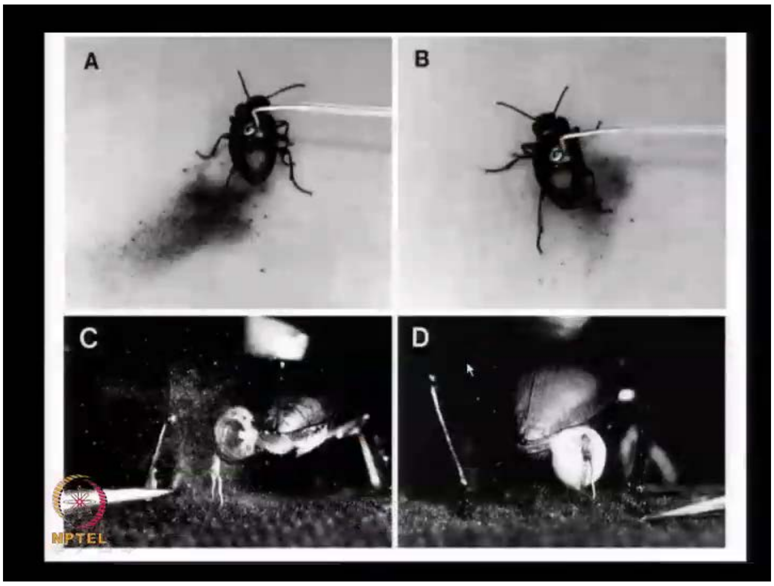

And if you get to see what really happens, let us go back. This is again about squirting, this beetle, this is the wrong or something like this you are making it squirt out in this direction, may be making it squirt out the hot gases in this direction and so on.

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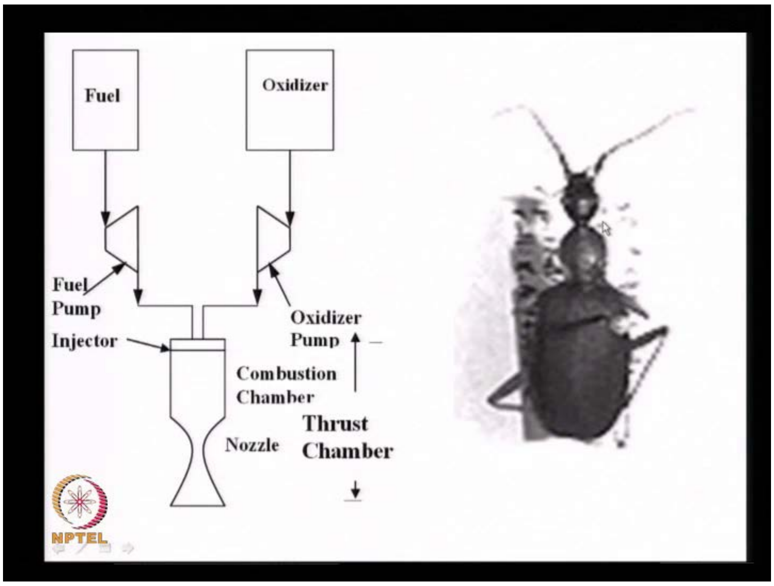

And if you look at what this beetle does, may be a chamber containing oxidizer, a chamber containing fuel, a third chamber in which it reacts and forms hot gases and squirts it out. Well, a liquid propellant rocket consists just a fuel in a tank, an oxidizer in a tank; you pump the fuel and the oxidizer into a chamber. And how do you pump it?

You pump it at high velocities through an injector may be you break it up into fine droplets; you vaporize it which is all happening in the third chamber over here. And then you have combustion taking place and you expand through the nozzle and this thing of an injector a combustion chamber. And the nozzle is what creates a thrust, it is also known as thrust chamber. And therefore, a liquid propellant rocket consisting of all this gadgets is nothing very much different from the bombardier beetle which is there in nature.

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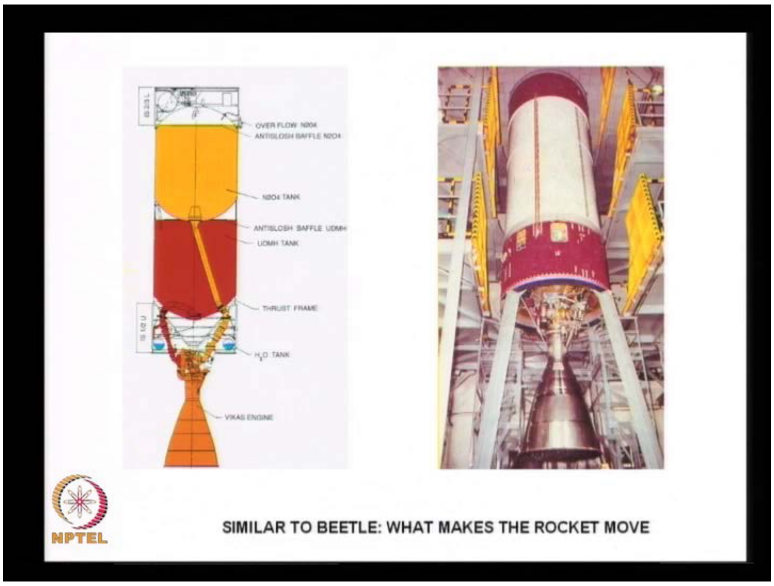

And therefore, I think we should learn to look at nature and understand more about nature. And say now we come to an to a large rocket, what does the large rocket consists of? This consists of N 2 O 4 as the fuel and u d m N t O 4 as the oxidizer I am sorry, and U D M H as a fuel. And what is done is you squirt out through from the tank, through pump you force the N 2 O 4 into the chamber, you force the U D M H into the chamber make it burn over here, expand it through the nozzle and this is what a liquid propellant rocket consists of. I show the outer casing of this over here, may be you have the N 2 O 4 tank over here inside the casing, you have the U D M H tank at the bottom, you have a series of pumps over here which push the propellant into the chamber and you got this. Well, this is the liquid propellant rocket which is during much akin to what is the mechanism by which the beetle generates hot gases.

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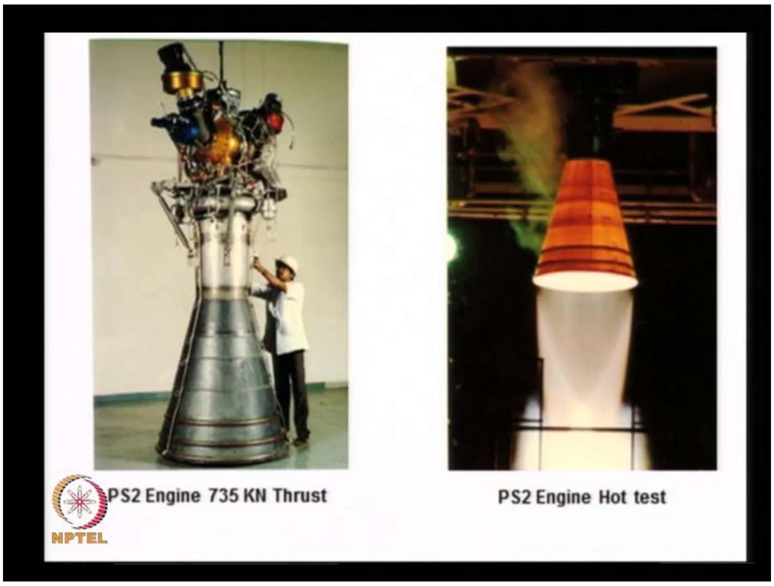

Well, this is all about it. Let us I thought maybe we should at this point in time itself look at few more pictures of this. Well, this is the engine which I just now showed you a liquid propellant rocket engine which is may be much taller than this man over here, this is the combustion chamber, this is the pump, this is the nozzle and this shows the rocket firing.

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Well, you know the same engine I show here in a slightly larger one in which I carry more propellant. I have the oxidizer over here, I have the fuel over here, I have the pump over here pushed at and it generates thrust through the particular nozzle.

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Let us take one more example. If instead of using N 2 O 4, as what did we say? In this particular, rocket which I just now showed you.

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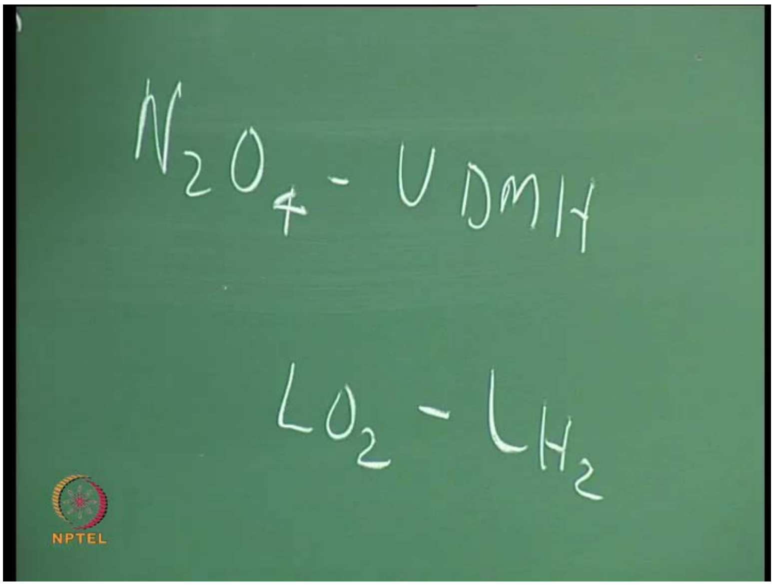

The oxidizer was N 2 O 4 and the fuel was U D M H. Well, we also talked in terms of fuel could be liquid hydrogen; the oxidizer could be liquid oxygen. And when I carry the propellants like liquid oxygen and liquid hydrogen well, liquid hydrogen is not very dense, I have a huge tank. I have this liquid hydrogen here, I have liquid oxygen here, I have a pump over here, I push it into the combustion chamber and it burns and this is what a cryogenic liquid propellant rocket is like.

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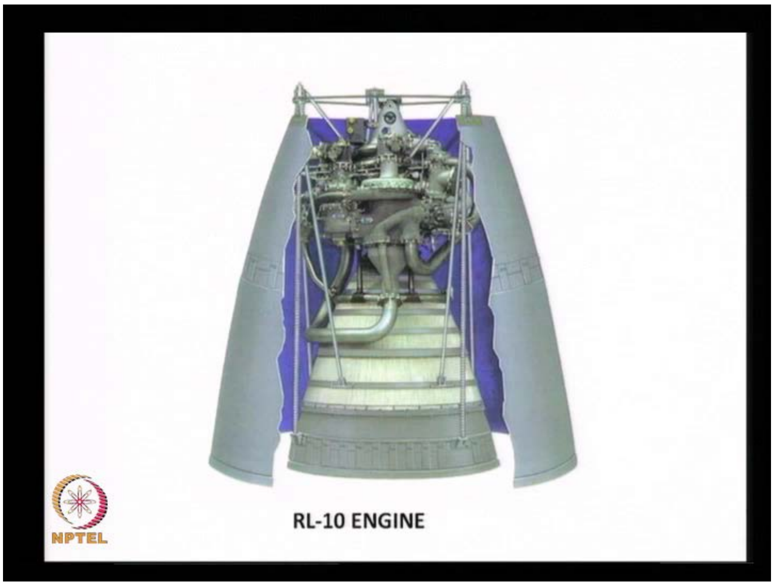

Well, I will cover this particular rocket; I was particular to show this, this is known as an R L 10 engine. This was the first cryogenic engine developed and this was in United States. This is was in the period 1960s and here again here; you have the pump mechanism pushing I did not show the tank over here, pushing the liquid hydrogen, liquid oxygen into the combustion chamber which is here. And you see the nozzle is a relatively large portion of the liquid propellant rocket, I think this gives us some feel for the sizes which you are talking of.

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Well, this is all about things which I wanted to show, I show the U D M H N 2 O 4 rocket here. This is the chamber, this is the nozzle and these are the pumps supported.

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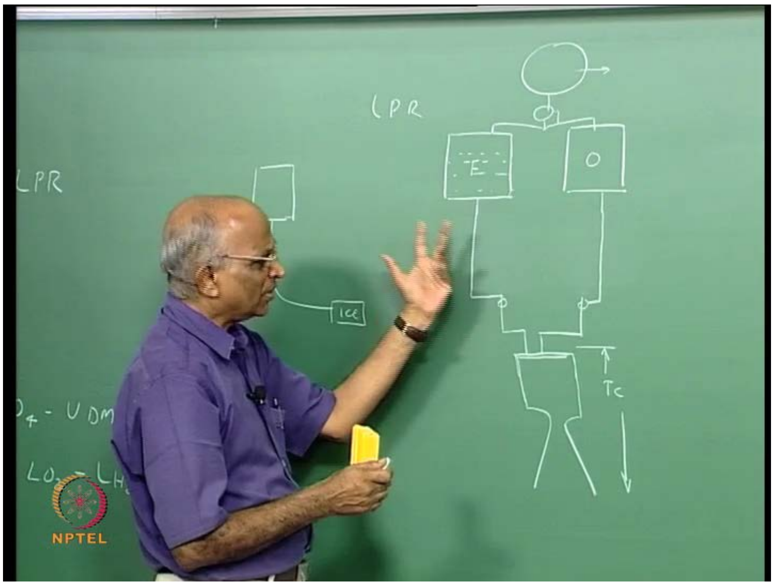

Therefore, what is it we infer from this few example which I have just now shown you. All what we infer is well, in case of a liquid propellant rocket, all what we need is something like a fuel tank, maybe we need an oxidizer tank, maybe I need something like a pump from low, small value of pressure. I increase the pressure, this tells me a high pressure, this tells me a low pressure. The magnitude shows the incoming pressure, may be the incoming pressure should be even smaller. The outgoing pressure should be much larger. I push it into a chamber and I cannot just push it, I have to break it up into particulates.

That means, I have something like an injector which allows the required quantity of propellants to come in break it into droplets. And I have chamber wherein reaction takes place and then I have this huge nozzle wherein I expand the gases. Well, this becomes the liquid propellant rocket, maybe I have to put some valves here to start the combustion to stop it whenever I want. And maybe I have let say the liquid fuel over here, the oxidizer over here and here you have the thing like this thrust chamber over here wherein, high pressure gases are formed and thrust begins to build up.

Now, you will immediately ask me a question, why do I have to have pumps in the first place? After all I have supply the fuel, why not I supply it, maybe I remove the pumps, I do not need a pump may be directly like what when we do an experiment using diesel combustion and an I c engine. I just have something like a overhead tank may be on the wall, I put a diesel tank and I directly take it and connect it to the I c engine for an experiment. Why not I directly connect the fuel and oxidizer and may be to push it through, maybe I can have something like a gas bottle here, a bottle containing high pressure gases.

And over here I put a pressure regulator in which case I reduce the pressure, maybe I have a reduction mechanism, I supply the gases at low pressure over here. In other words, I put a pressure regulator; I have a high pressure source of gas, why I have high pressure? I can have a smaller gas bottle and I pressurize the fuel at high pressure, I can send into the chamber. Therefore, I need not always have a pump, but to be able to understand whether pumps are really required. I need to do a little more exercise on this. Let us see what is required, let me again re-plot this.

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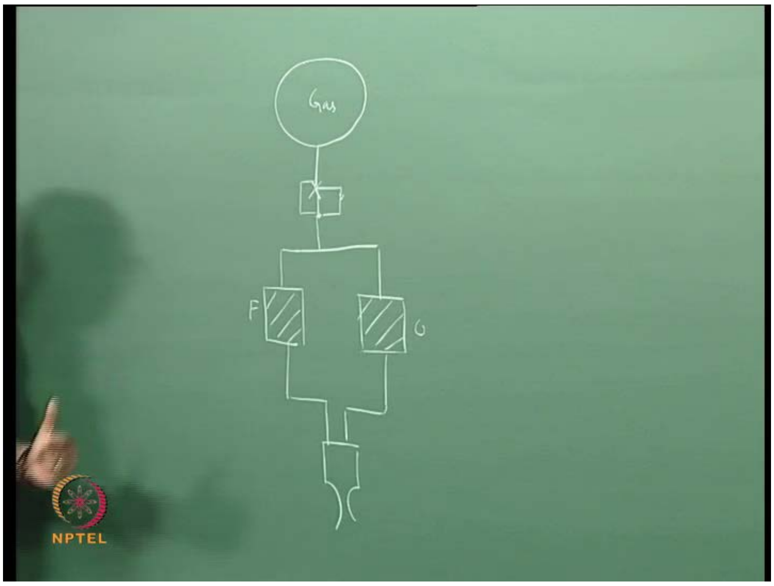

I tell myself, I have something like a gas bottle which stores gas at high pressure. I have something like a pressure regulator at downstream, and what does the pressure regulator do? Maybe from high pressure I can store gas at maybe 30 M P a, maybe 300 bars to 400 bars. But I do not want such high pressure therefore, I want much lower pressure maybe 10 M P a or 1 M P a. Therefore, I put a pressure regulator which senses, which will reduce the pressure by the particular opening, it is a feedback control therefore, may be as it is controlling, it is also connected over here. And then I connect this gas to the fuel tank to the oxidizer tank which are full of propellants and then I bring it into the combustion chamber over here.

What is it I am talking? I am talking of having a high pressure gas bottle. I regulate the pressure to a lower value and push the fuel and oxidizer into the combustion chamber. Well, this becomes something like a I just use a cold gas, a gas high pressure gas and this I call as a regulated gas pressure fed system that means, it is always you know after all I am interested in this. I started with a pump let see under what conditions I would really require a pump over here, under what conditions I can use a regulated pressure system. Well, it is not always necessary to have a gas bottle and all that, I can still think in terms of a different configuration.

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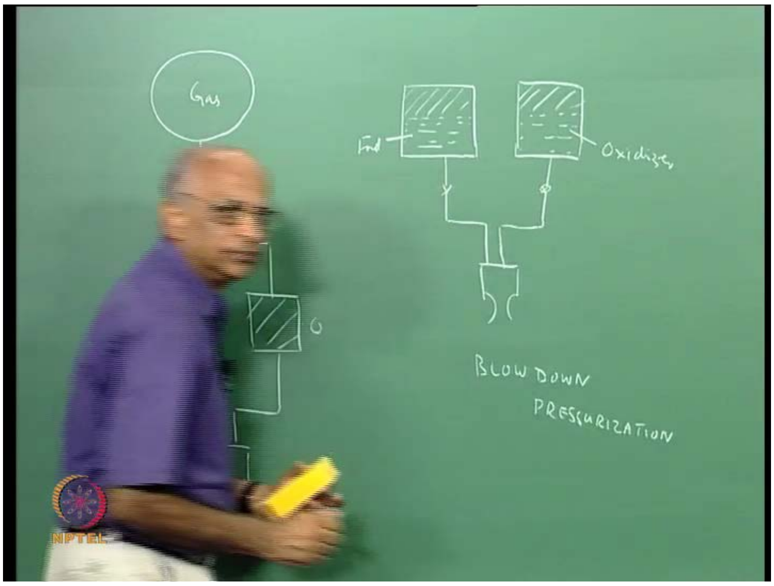

Wherein, I take a tank as such may be a fuel tank, may be an oxidizer tank, I do not even I do not fill the propellants fully in the tank. Let say this is the fuel tank liquid fuel here, I have I fill it with oxidizer liquid oxidizer over here and I directly bring it over here and supply to the chamber. But how do I push it? I fill gas over here, I fill gas that may be high pressure over here and then I put may be a valve over here I start this valve, I start this valve, immediately propellant flows. When I want to stop it, I close this valve. And therefore, this becomes may be the gas is contained in the tank itself and it blows the propellant into it this is known as a blow-down system. (No audio from 16:15 to 16:26) Therefore, what is it I have been talking of?

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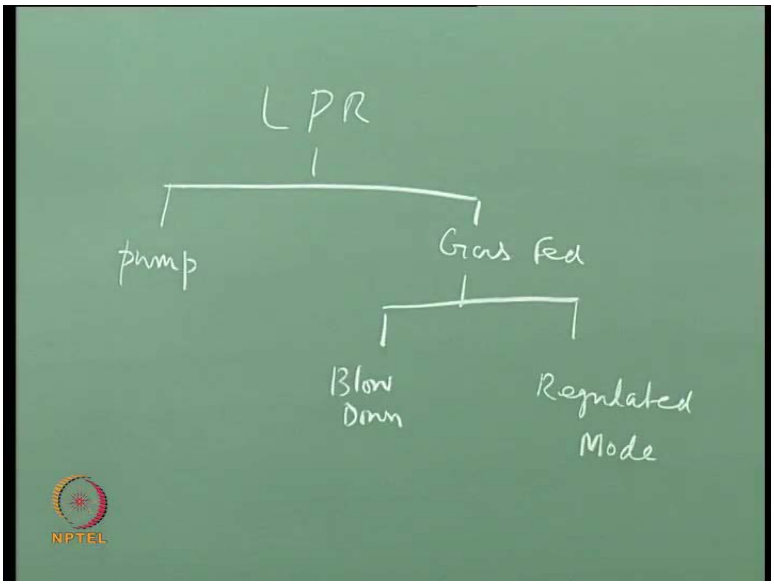

We tell ourselves, in the case of the liquid propellant rockets, we need to supply the propellants; we started looking at the beetle and told ourselves well, a pump may be required. But we also told may be a gas, a cold gas at high pressure is possible. This gas can be directly filled, and what will happen when it blows down? The pressure keeps decreasing and therefore, the thrust keeps decreasing. Whereas, if I give something like a regulated gas I maintain constant pressure over here and therefore, I get a constant thrust. Therefore, the gas fed, high pressure gas fed could either be a blow-down mode or in a regulated mode as such. You know but, you know there are we cannot rule out that this is not required. For instance if you have a satellite which is sitting in space, let say inside spacecraft I will show you the small model which I happen to have of the satellite.

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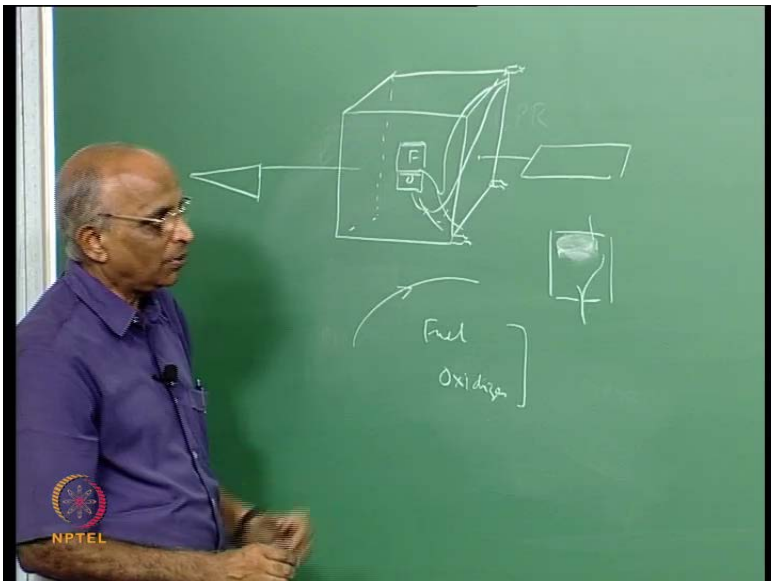

You know let say you have the satellite like inside is something like a box structure consists of a box and you have something like the solar sails over here. And since when the light falls on the solar sails, you know it creates pressure. We will study this method of propulsion towards the end of our classes. You have to balance the pressure from the sunlight falling on this; you put something like a balance over here such that it does not get tilted over here. Then to control the attitude we had told ourselves, we put small rockets on either on the different phases over here, and how do you supply propellant to this, inside this? Inside this structure I put something like a propellant tank and oxidizer tank, at the bottom of this oxidizer tank I have a fuel tank may be in the common bulk head.

That means I have a single connection over here, this could be fuel, this could be oxidizer. I could have put some gas pressure over here and make sure that this gas pressure is connected to lines to may be this rocket over here, may be this rocket over here, and so on. Whenever I want this rocket I open this valve and it fires. And this is the model I brought of this particular blow-down mode. And if you are going to see so this is how the spacecraft the inside spacecraft looks. See, you have this is the central box inside it there is a chamber in which I have the tank, fuel tank and oxidizer tank. And these red knobs what are shown are things which correspond to the thrusters or rockets liquid propellant rockets.

And what is done is, whenever you want the rocket to be fired you just open the valve it the tank is already pressurized. The liquid fuel and liquid oxidizer flows into these thrusters and they generate thrust and that is how you control it, and this is how the liquid propellant rockets are used in spacecrafts also. But there is a problem, whenever I have fuel and oxidizer and a spacecraft is sort of revolving around at a constant velocity. We told ourselves well I have in this frame of reference it has a centrifugal force which is balanced by the gravity. Therefore, the there is no mass for this and it creates new problems.

Therefore, we have to see under weightlessness how do we supply the propellant therefore, this also may be we will take after some time. Therefore, this also requires that means, you have to supply fuel and oxidizer then they are in a state of weightlessness. That means if I put a propellant in a tank that the propellant may sit on top, it may not really come at the bottom. And when I pressurize it with the gas, the gas may come out the liquid may not come out. That means supply and a propellant when I am in a state of weightlessness is again going to be a problem. May be we will take a look at it, but right now, let us take a look at what constitutes, let say a gas fed system which either be blow-down mode, regulated mode and then let us come back to the pump.

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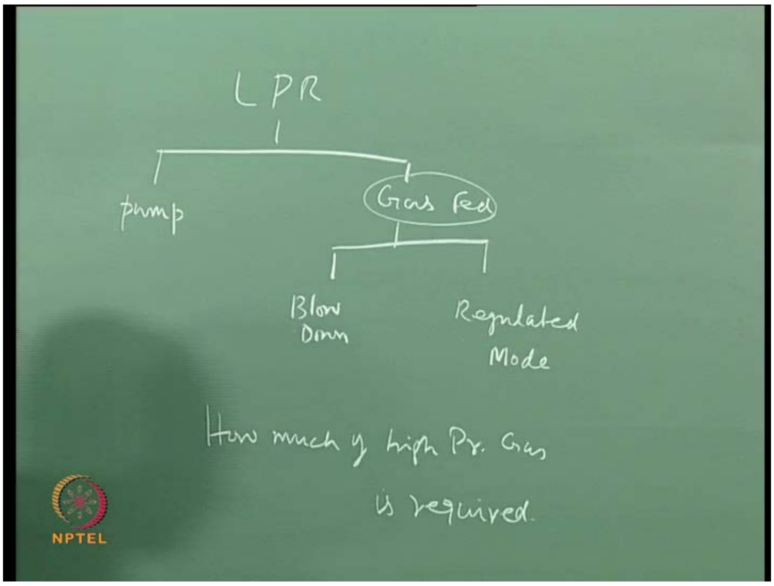

Let see if in between these two anything else is also there therefore, to be able to do this, let us first try to find out how much gas, how much of high pressure gas is required. (No audio from 21:12 to 21:19) See, first thing we have to supply the propellants I know once I give the thrust. I know what must be the mass flow rate of propellants and how do I calculate it out let us refresh it ourselves again.

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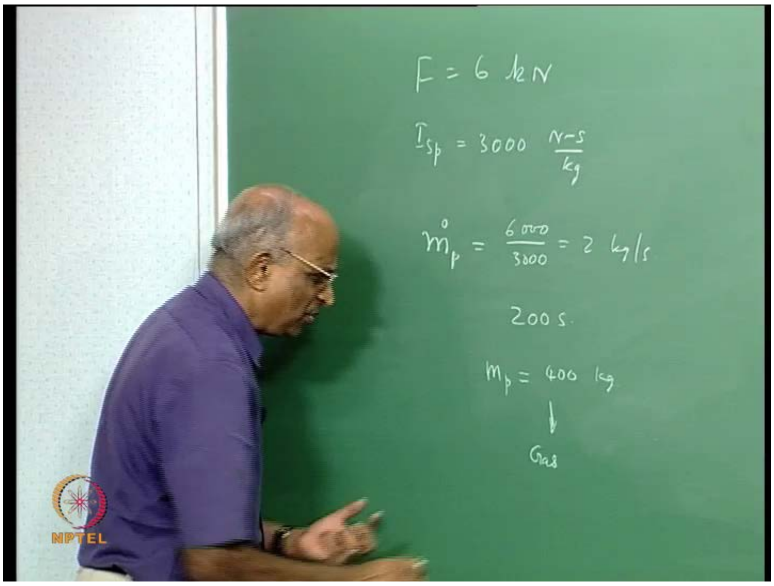

We say suppose, the thrust of the rocket we will take an example a 6 kilo Newton. Let say the specific impulse of the rocket is equal to 3000 Newton second by k g then I know the mass flow rate of total propellant fuel and oxidizer is equal to 6000 Newton divided by 3000 which is equal to something like 2 k g per second. To be able to supply this 2 k g per second may be the rocket has to fire for 200 seconds let say, we take a small firing rocket for a small time of firing let say 200 seconds, then I need to supply a total mass of something like 400 k g during the 200 seconds. We talk of 6 kilo Newton, 6000 Newton, this is 3000 Newton per second, 2 k g per second this is the total mass of propellant which has to be exhausted. I want to know how much gas is required, how much mass of gas is do I require 1 k g, do I require 100 k g because if the gas requirement is large, well the rocket cannot takeoff.

Let us try to estimate it, and how do we estimate it? We again follow the same figure, but now let us simplify it. Let us simplify this and say well I have gas pressure and we also told ourselves well gas can be stored at fairly high pressures.

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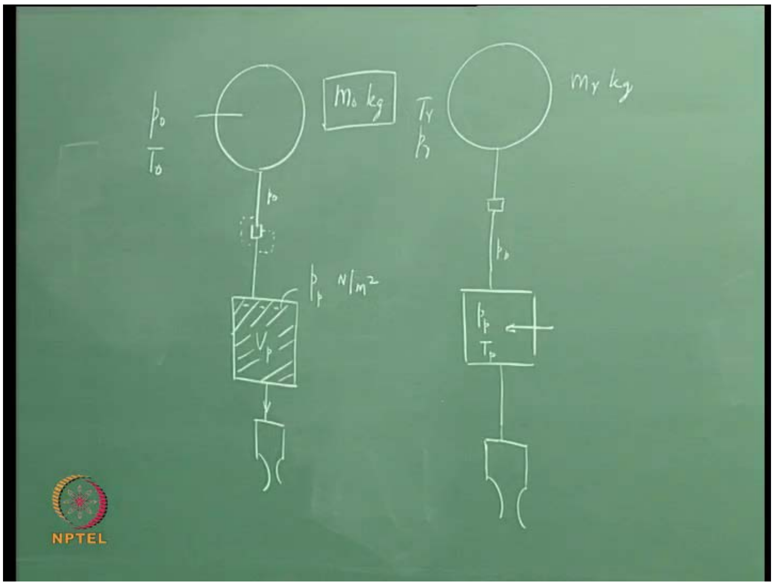

Let us plot it out, I have a gas bottle it contains let say m o kilograms, m 0 kilograms of air or gas, what is required I must also find out which gas will do my job. Well, let say it is at a high pressure P 0 and at the room temperature T 0 because I do not want to at this point in time say I going to need a hot gas or a cold gas. May be when I derive the expression, it will be also clear to us what type of gas is required and what must be the temperature of the gas. What I do from this high pressure source? I put a pressure regulator here and I reduce the pressure from the value of P 0 and it must communicate the two tanks I put together. Let say the total volume of propellant is V P and this is what must be supplied to the thrust chamber over here.

Let us say the pressure at which I would like to supply is let say this is my surface of the thing I need a pressure P p over here, P p let say Newton per meter square a Pascal. And I want I reduce the pressure from P 0 to P p in this type of regulator, I reduce the pressure from P 0 to the value P p. Now, my point is how do I find out the value of m 0 k g. I think it is a straightforward thermodynamic problem, but before doing this problem it is also required for us to put some other things down. Let us do a general problem, let say at this point in time when I start the work, I have the quantity of propellant liquid which is available is V P. When I finish my exercise, the quantity of gas which is available is going to be it I use some gas for pressurization.

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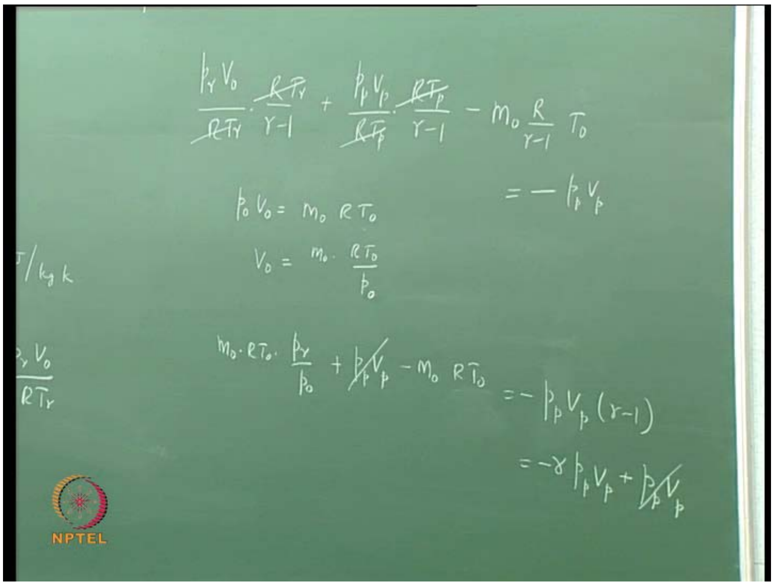

Therefore, at the end of operation, let say m r it is reduced, so much k g is left. And the temperature here is t r, the pressure is p r, and then at the end of it again I have the same system over here, the same tank over here, all the propellants are expelled, it is now gas over here. And since I am through the regulator over here since, I have reduced the pressure to P p over here. When the propellant has just got out of it, it will be filled with gas at a pressure P p and the temperature. Since, it is slow depletion or fast depletion, it reaches the temperature of the propellant the temperature will be T p over here.

In other words, what is it? This is my initial condition, let me make the figure complete. What is it I am telling? I have exhausted or pushed out, a volume of propellant V P and now, I am left with after pushing out is there, the gas has expanded, occupied this volume in addition to this volume and this is my final condition. I want to write an equation and determine the value of m 0 k g what is required. How do I do this problem? May be we have done such problems in our thermodynamic subjects earlier. Let us write just try to write an equation for it, and try to determine the value of m 0. I want to ask you what is happening; let say the system does not have any heat transfer. Let us make an assumption that the tanks are fairly insulated, gas bottle is insulated there is no heat transfer taking place. And therefore, I ask myself what is the work which is done by the gas in pushing out a volume V P of the propellants.

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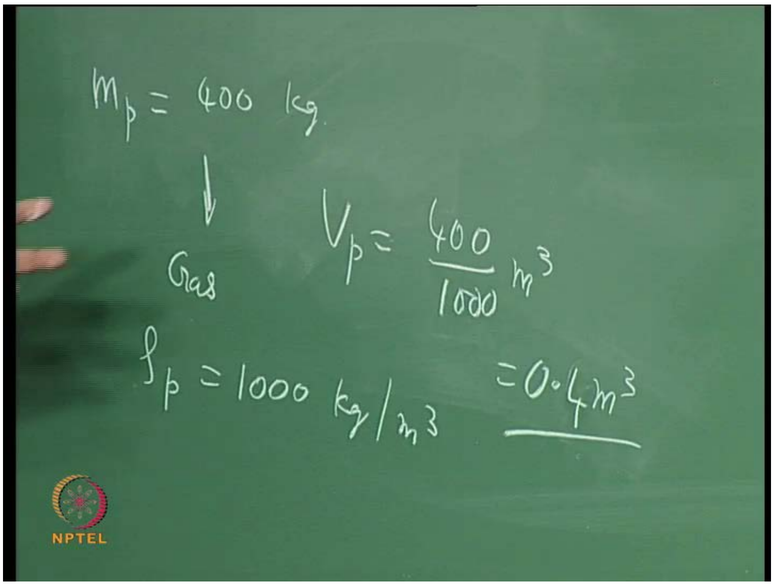

Let us calculate V P over here for this particular problem, V p if I take the density of the propellant to be same as water, density is equal to 1000 k g per meter cube that is the density of water 1 gram per c c. And therefore, the volume V P over here is going to be 400 divided by 1000 meter cube which is equal to 0.4 meter cube. In other words, for this rocket may be I have to get rid of 0.4 meter cube at a given value of pressure.

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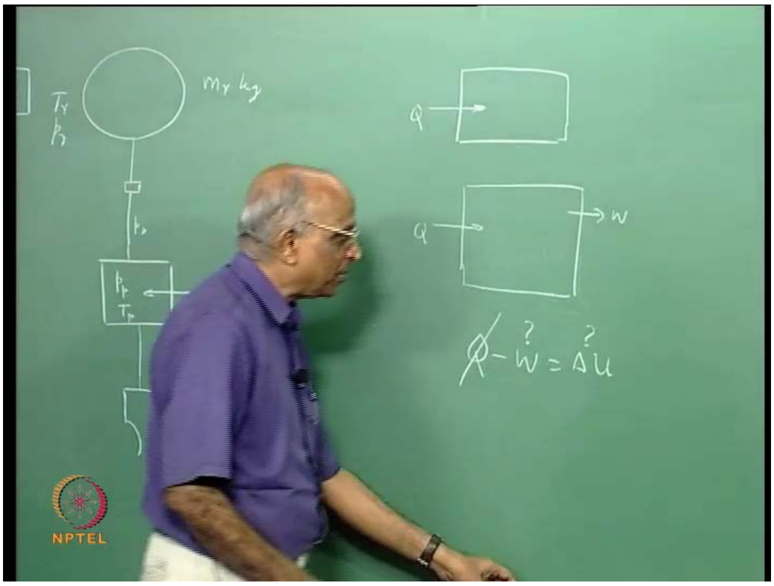

Now, before I complete that problem, let us try to generate an expression and see what is the value. We tell ourselves supposing I have a system, let say a system like this, this is my initial state of my gas over here, the final state of my system is this. In which the gas has come from here and moved over here. I tell myself Q is adiabatic well Q is there, the system does some work at the boundaries, then I can write Q minus W is equal to the change in internal energy for a system. Something is getting in, some work is being done and that change is what is the internal energy. Therefore, now I need to say well I take an adiabatic system Q 0 I need to find out the value of W, and I need to find out the value of change in internal energy.

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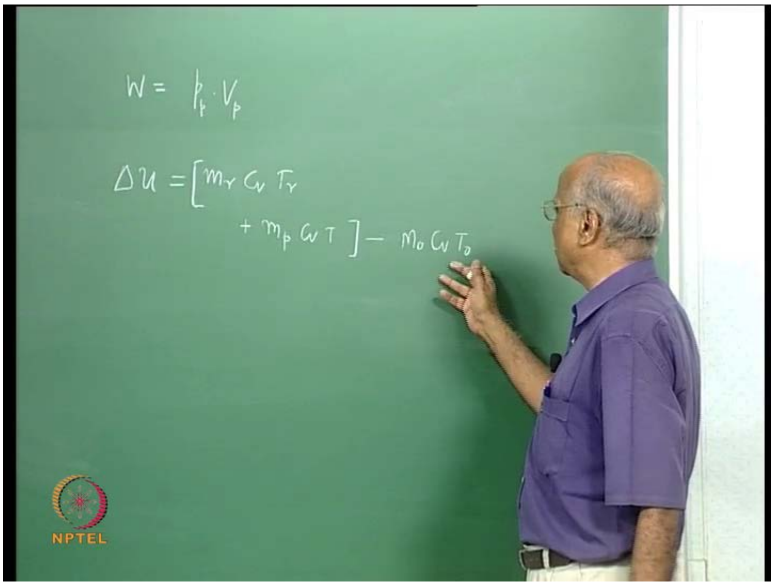

Let us write the expressions for these two. The work done by the gas is in expelling the liquids and therefore, what is the value of work, can we say? Well, I have a constant pressure which is applied over here the displacement is V P, the work done is equal to P p, the pressure into volume of the liquid. Is it ok, what is the change in internal energy final minus initial? Well, finally, I am left with m r of the gas over here, we know that d u by d t let us put it down over here is equal to C p where, u is the specific internal energy C V I am sorry. Because and d h by d T is equal to C p well, we are talking of internal energy therefore, u is equal to C V T. And therefore, d u is equal to the final gas m r which is available into C V into T r. This is the final mass which is available; we say it is at a reduced pressure and the reduced temperature because it has expanded. Some gas comes over here plus I have gas which is the m p into C V into T, this is the final value of internal energy. I say that these volumes of the lines over here or plumb lines are much smaller than this and this therefore, I neglect it. And what is the value of the initial internal energy minus yes, you could tell me. What will be my initial value? Yes, m 0 into C V into initial temperature. I need to solve this equation and find out this after knowing that minus W is equal to delta u let us find that value.

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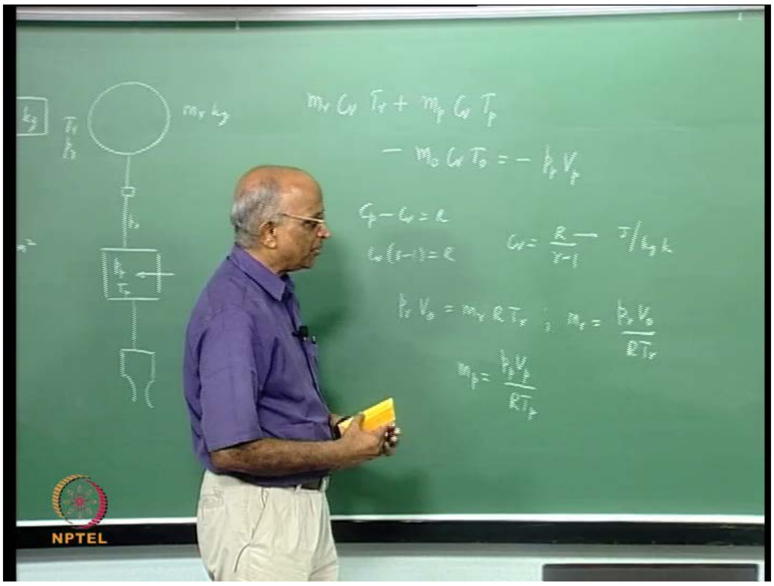

Maybe I use this, this part of the board. What I have? I have m r into C v into T r plus m p into C v into T p temperature of the final propellants should have been T p over here minus m 0 C v into T 0 is equal to minus W minus P p into V p over here, is it all right. Q minus W is equal to the change in internal energy. I want to solve this, to be able to solve this let us see what C v is, we know C p minus C v is equal to R. And therefore, C v into gamma minus 1 is equal to R, or rather we have C v is equal to specific gas constant divided by gamma minus 1 where, R is the specific gas constant has units of Joule per kilogram Kelvin and C v therefore, has units of again Joule per kilogram Kelvin.

Now, what is the value of m r? From the gas equation, we have p r into V 0 that is the volume of the tank is equal to m r into R into T r. Or rather I can write the value of the mass, final mass after expansion has taken place in the tank and the mass of gas in the tank is equal to p r into V 0 divided by I have R T r, is it all right. Similarly, I can write an expression for m p and what will m p come out to be? m p should be equal to P p into V p divided by R into T p over here.

I need to find the value of m 0 therefore, let us not touch this. Therefore, let us substitute these two values of m r m p and the value of C v in this expression and try to get the value of m 0 coming out. Let us say m r is equal to p r into V 0 divided by R T r and C v was equal to R divided by gamma minus 1 and into T r plus similarly, I get P p V p by R T p into R again I get the value of T p divided by gamma minus 1 minus I get the value of m 0 into R divided by gamma minus 1 into the value of T 0 over here this is equal to minus P p into V p over here, is it all right.

Now, I find that R T r, R T r cancels R T p R T p cancels. And now if I were to simplify you know I do not know the value of volume because volume is related to mass, I can write P 0 V 0 that is the initial condition of gas before starting over here is equal to I can write it as equal to m 0 divided by R T 0. Or rather I can write the value of V 0 as equal to m 0 into R T 0 by P 0. I substitute this expression after a volume is equal to mass into m r T divided by p over here, I substitute over here. Take gamma minus 1 on the right hand side because all the three have gamma minus 1 and therefore, I get m 0 into R T 0 into p r by P 0 is the value this reduces to plus I have P p into V P over here minus I get m 0 into R T 0 divided by gamma minus 1 is equal to minus P p I am sorry, I should not have put because I am going to remove gamma minus 1 here minus P p V P divided by gamma minus 1. This right hand side now reduces to minus gamma p of p V of p minus p of p into V of p plus because minus and minus becomes plus therefore, immediately this and this get struck off. And now we are able to get an expression for m 0 let us put it over here.(No audio from 36:12 to 36:19)

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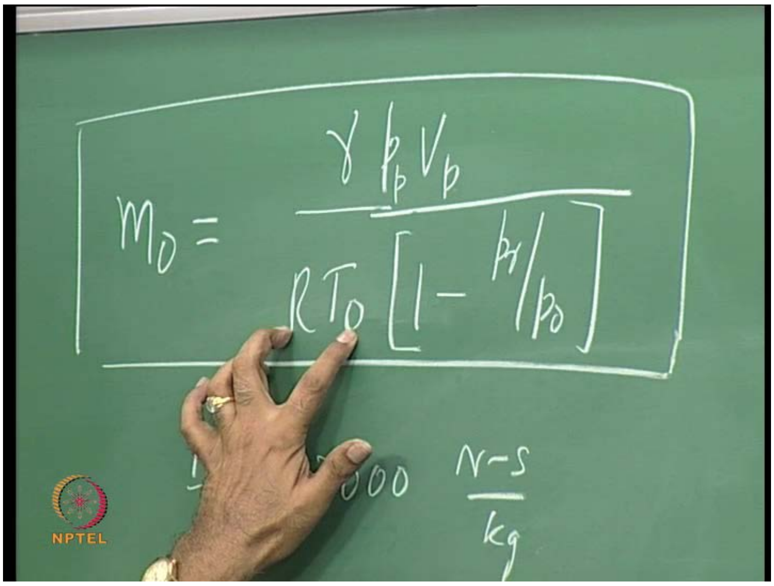

Let us collect the similar terms I get R T 0 which will come at the denominator. I have in the numerator the value gamma on the right hand side therefore, what is that gamma P p V p into I have 1 minus value of p r by P 0. Please check this how did by we come to this, we have m r T 0 m r T 0 we have p r minus 1 is equal to minus gamma therefore, I take the I change the sign on both side, I get gamma P p V p into R P 0 which comes in the denominator into 1 minus p r by P 0. Therefore, this becomes my mass of the gas which is required.

Now, I want to examine how much is this gas now what is this expression, let us you know whenever we derive an expression, we must take a look and see under what conditions this holds good. Let us do that I do not need this anymore. I say had the process being isothermal, what would be gas I require? m 0 will be equal to P p V p by R T 0 because it is a isothermal.

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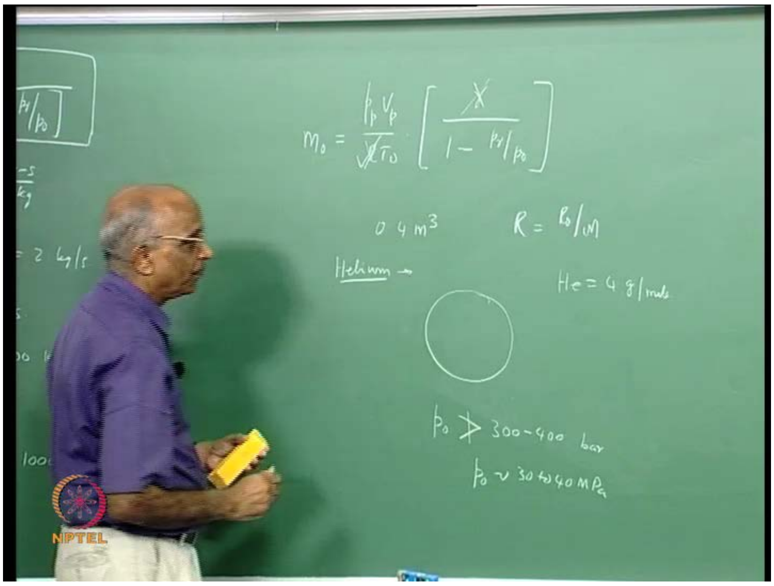

Therefore, what happens when gas is expanding and that also irreversibly? I get under isothermal expansion I could just have P p V p by R p 0. And due to the expansion process I have an amplification taking place 1 minus P r by P 0, and this is because of the expansion process which is taking place. I am writing the same thing P p V p by R T 0 because m is equal to p V by R T 0 isothermal, and then this is the multiplication factor.

Now, I want to find out may be for this engine which we said is 6 kilo Newton. I want to find out the mass of the gas which is required let us go for one example and then we can extend it for different pressures and different thrust. Let say in this case the volume is equal to 0.4 meter cube now, how much gas do I require? Well, this expression also tells me, what is the type of gas, which I require? Do I require a light gas or a heavy, what does this expression tell me, can we all infer something from this, should I pressure pressurize the initial volume with a high molecular gas, low molecular mass gas or at a high temperature or under what conditions should I do? All what I can tell you is the value of p 0 is limited because I need a gas bottle which can hold certain pressure and that pressure cannot be greater than around 300 to 400 bar. Because beyond that to make something hold such high pressure gas is difficult therefore, normally the P 0 is around 30 to 40 M P a, this is bar over here.

Now, all that I know is here P 0, how can we choose the other parameters like gamma R and all that does it tell me what is the type of gas which is required? We do one more exercise let say R is equal to universal gas constant divided by the molecular mass 8.314 by the molecular mass. If the molecular mass of the gas is smaller, I get a very large value of R. If I get a large value of R, I can have a smaller mass of the gas. Therefore, this immediately tells me the lighter the gas the better hydrogen is the lightest whereas, helium has a molecular mass of 4, helium 4 gram per mole. Therefore, invariably I would like to choose helium which is a light gas for my purpose. See, the expression is able to tell us what we are looking for this is one.

Second is well, but helium has large volume of gamma 1.67 compared to air of 1.4, but this is 1.67 whereas, R could be something like 4 and 28 seven times therefore, this is not that important, this is more important and therefore, I choose a light gas for pressurization. But this expression also tells me a higher temperature is suited because higher temperature means I have a smaller value of mass of the gas therefore, rather than choose a cold gas.

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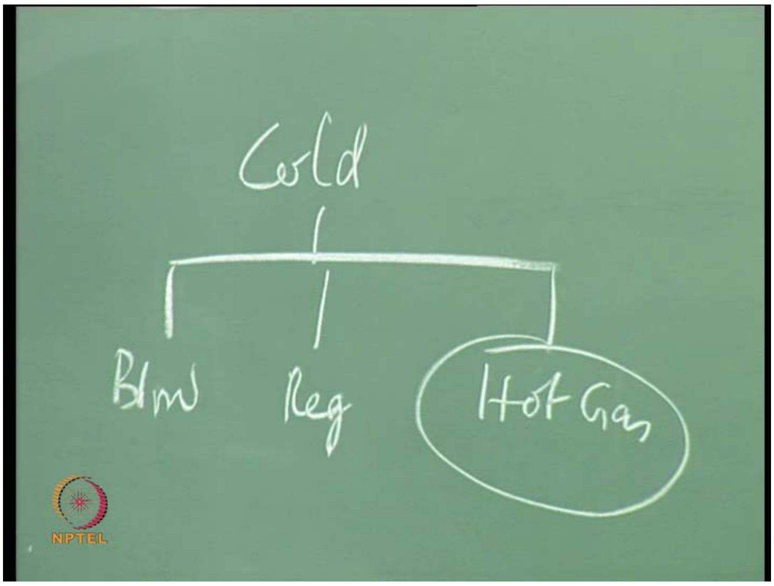

That means we initially said I have a gas which is cold for pressurization, why not use a hot gas, why not have some reactions taking place in the combustion chamber and do this. And therefore, this is also an option therefore, in addition to saying for cold gas I could have blow-down mode, I could have regulated mode, it is also possible for me to have hot gas. And hot gas is more efficient, but in practice it has been difficult several countries have tried it, but this has not yet found an application. But I think we should keep this in mind, I think in future this will be a strong contender for a for a gas pressure system.

Having said that let us do a small numerical problem to, what is the amount of gas? You know we should have some feel whether I need 1 kilogram whether I need a few grams.

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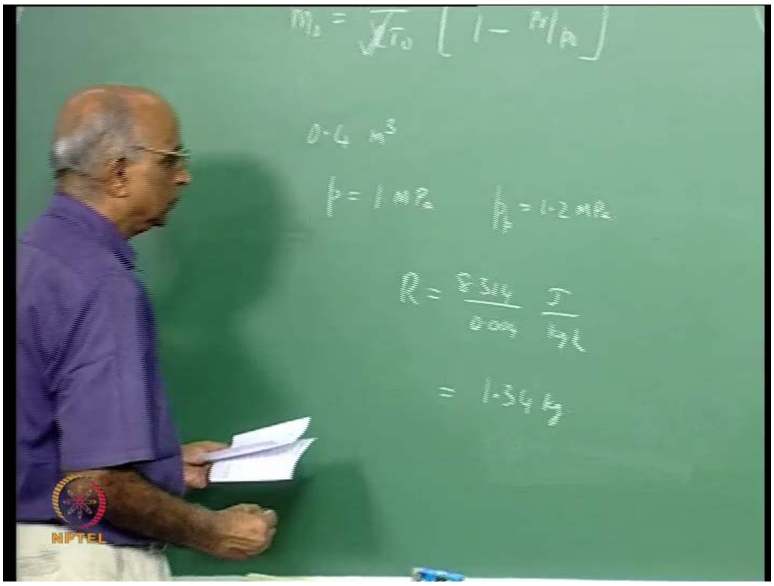

Let say for this rocket which is requiring a V p of 0.4 meter cube, let say the chamber pressure it is small chamber pressure let say 1 mega Pascal. If the chamber pressure is 1 Pascal, I have to force propellant into it let say P p is equal to 1.2 M P a therefore, I say yes, the final pressure the lowest p r is equal to the supply pressure over here. The volume is known or for the gas helium is equal to 8.314 divided by 0.004 so much Joules per kilogram Kelvin, this is known and I can calculate the value of mass. And this value of mass for this particular thrust when the supply pressure is 1.2 M P a works out to be something like 1.34 k g. Now, I want to slightly change it, I have the same rocket which is developing a 6 kilo Newton.

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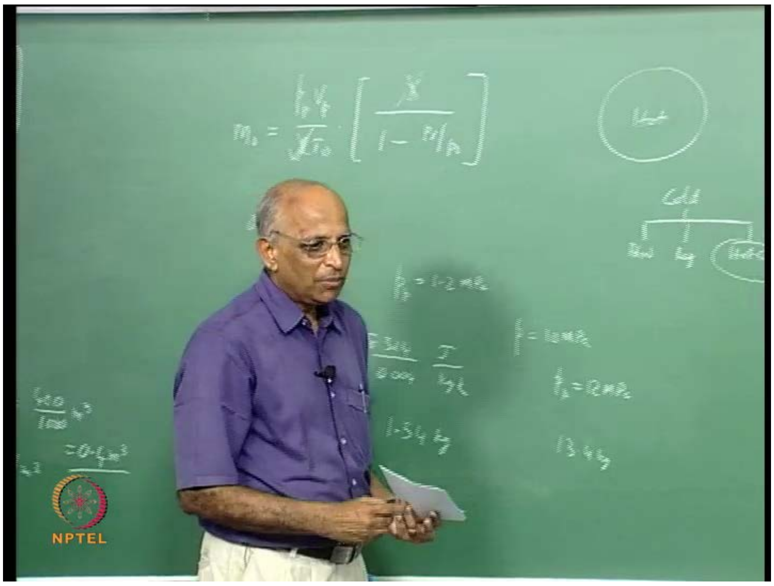

But the chamber pressure instead of being 10 bar or 1 a mega Pascal is now changed to pressure is equal to 10 M P a and the supply pressure therefore, becomes let say 12 M P a and therefore, the quantity of gas becomes directly 10 times that is something like 13.4 k g. Now, if I talk in terms of thrust which is much larger, may be 600 kilo Newton. The quantity of gas will be very much larger and therefore, we will have much larger quantity of gas. May be you should try this as an example, but let me summarize it through slides.

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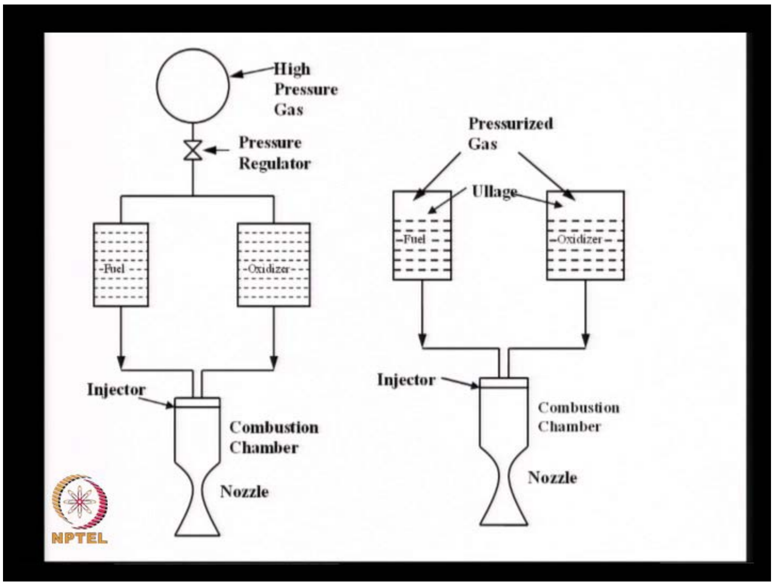

And what I do in the next series of slides is, well this is what we said as a regulated pressure system, this is something like a blow-down system.

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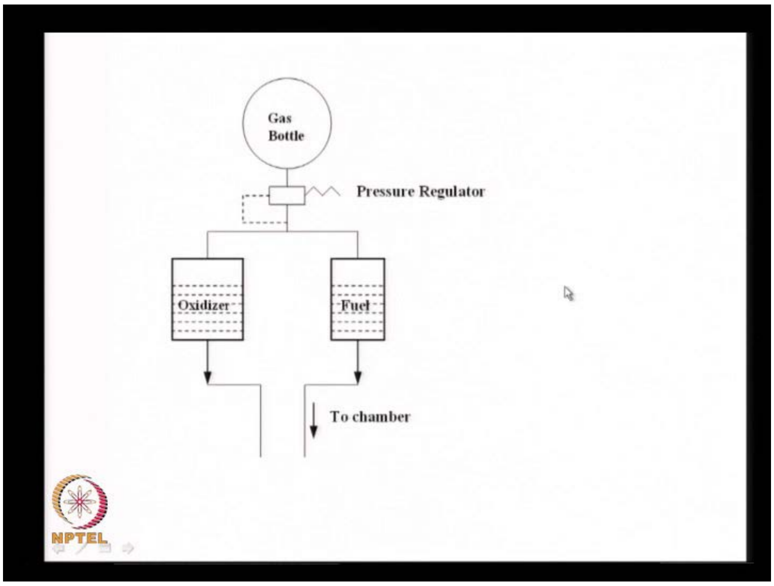

And we wanted to find the gas well we had the gas bottle we had the regulator oxidizer and fuel to supply over here.

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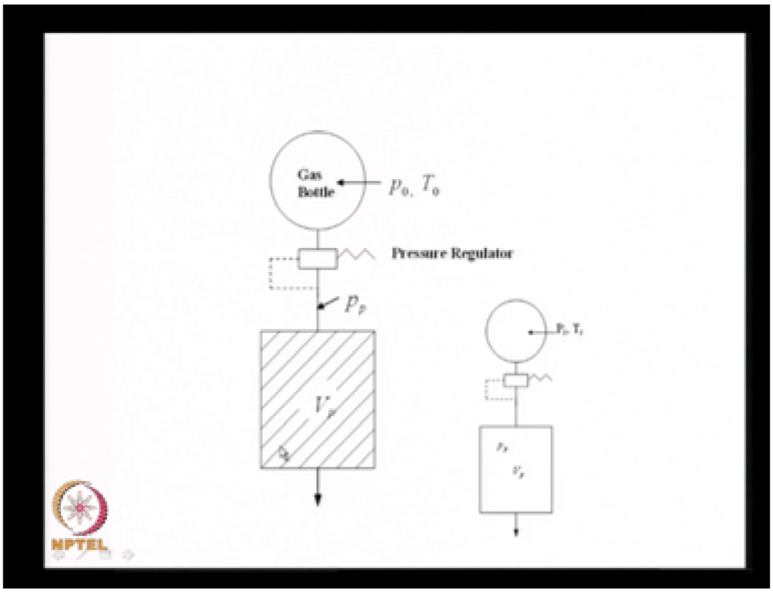

And we simplified it this is the initial condition, this is the final condition and then we went to a ground.

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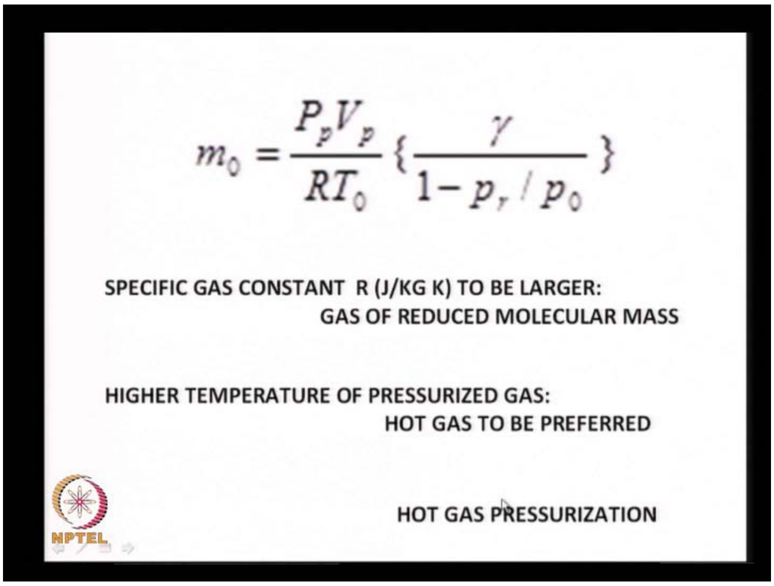

And said m o u mass of the gas required is equal to P p V p by R T 0 gamma by 1 minus p r by P 0 and then we found out that hot gas pressurization is an option.

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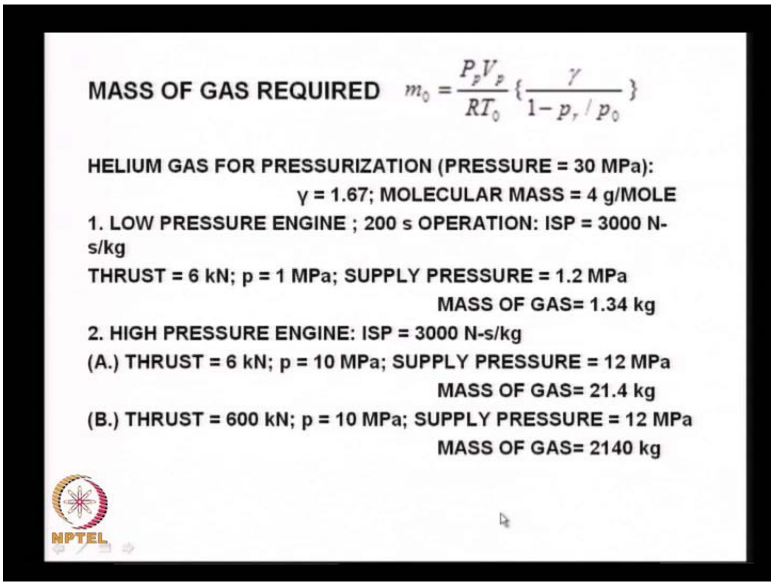

And then now we calculate the value, when I have a low pressure engine of thrust of 6 kilo Newton, the chamber pressure is 1 M P a the supply pressure is 1.2, the mass of gas required is 1.34 k g. Then the same 6 kilo Newton is operated at a high pressure of 10 M P a, the supply pressure is 12 M P a, the mass of gas becomes instead of 1.34 I should have written 21.4 may be somewhere may be I this factor I had removed therefore, it is not 113.4, but it is 21.34 may you all should check it at home.

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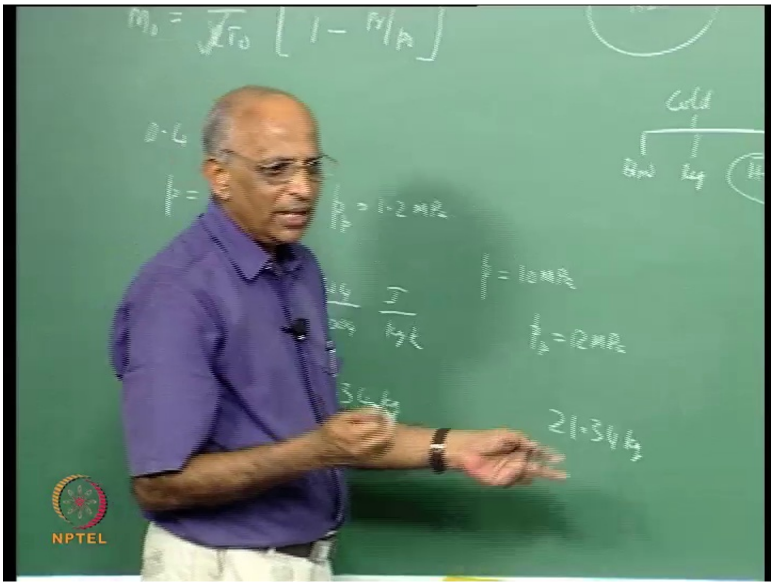

You see when the chamber pressure increase by 10, the quantity of gas is increased by almost twenty times. Whereas, if I have a high thrust engine of 600 kilo Newton at the same pressure value, the quantity of gas required is something like 2000 k g. And therefore, it is not humanly possible to have such amounts of gas being carried in a rocket and that is where it becomes necessary for us to have something like. Let us go back have something like a pump which can supply the propellants to it and that is why the necessity of a pump.

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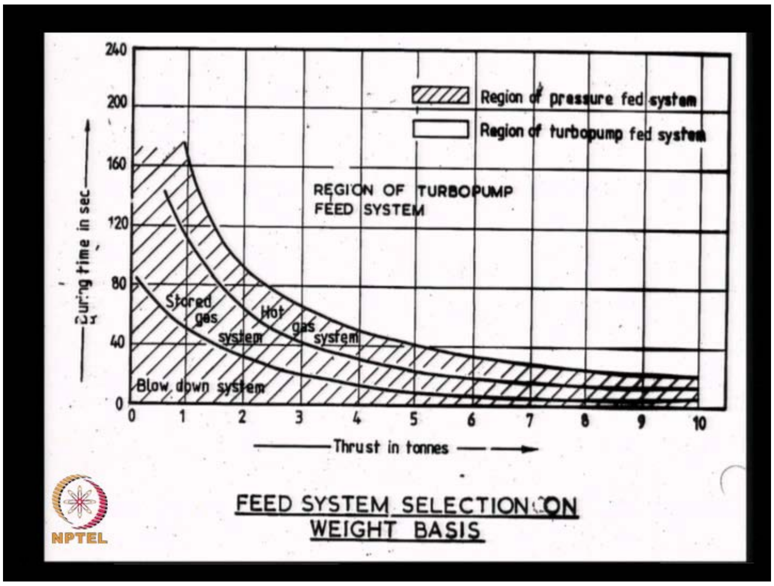

Now, if you like to go back and compare the different systems what we had, we talk of a blow-down, we talk of stored gas, we talk of a hot gas, we find when the thrust is small and the burning time is small. I can manage to have blow-down system like what was used in our inside spacecraft because I need very small thrust I operated low chamber pressure. Then I want to operate at slightly larger time, slightly larger thrust, may be something like a regulated gas system is required, but if I want still better may be a hot gas system.

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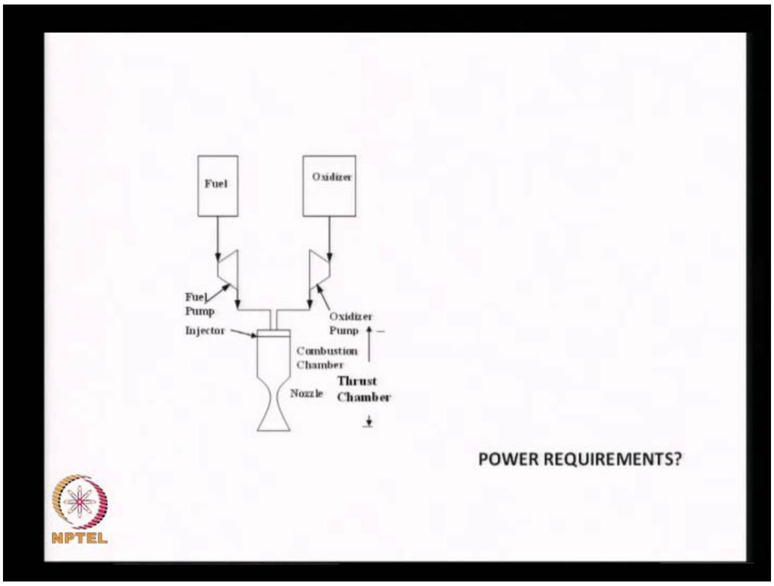

But beyond some thrust and beyond some burning time I need to operate in this region which can only be done using turbo pump or a pump system therefore, what is it we have been telling ourselves so far we said well the feed system could consist of different events or different possibilities.

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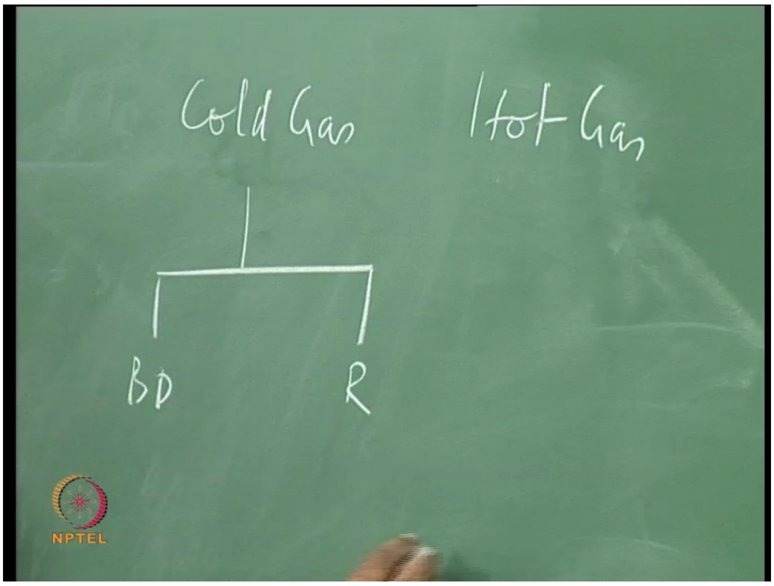

And what we said is we could have cold gas pressurization that means, I have a gas bottle containing or something like a hot gas, the cold gas could either be as blow-down mode or in a regulated mode. But if that duration of the rocket fires for a longer time and if the thrust is large or the chamber pressure is large, I essentially need a pump to take the fuel from the tank into the chamber and this is what we must remember. Therefore, what is it we do therefore, maybe I need a pump system now let us go back and calculate what is the power of the pump which we require in this case, let us just do that small exercise using the same numbers what we had. Let us let us take this example.

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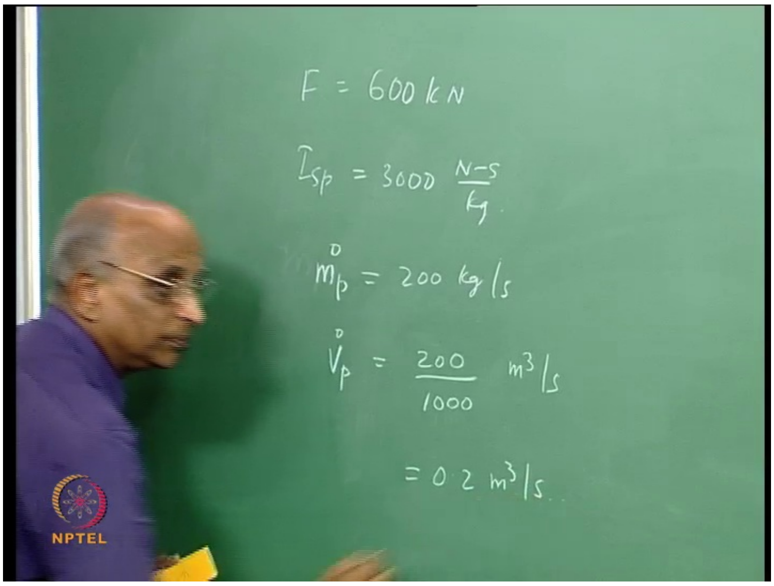

The thrust of the engine is equal to let say 60 kilo Newton or 600 kilo Newton that is how that engine worked I showed U D M H N 2 O 4 as a thrust of around 600 kilo Newton. And I say the specific impulse is equal to 300 Newton second by kilogram therefore, my mass of mass flow rate of propellant is equal to something like 200 k g per second. Mind you, keep this numbers you know let us have some familiarity for numbers because we must be able to think in terms of numbers 600 1000 divided by 3000 over here it is equal to 2 therefore; I have 200 k g per second. Therefore, if I have to talk supply this let us again take the density as same density of water therefore, the rate at which the volume has to go is something like 200 divided by 1000 meter cube by second which is equal to 0.2 meter cube by second. What is the power required for a pump to supply 0.2 meter cube per second at a given pressure? Let us take the same value of pressure, let say pressure it has to supply at a pressure of let say 12 mega Pascal.

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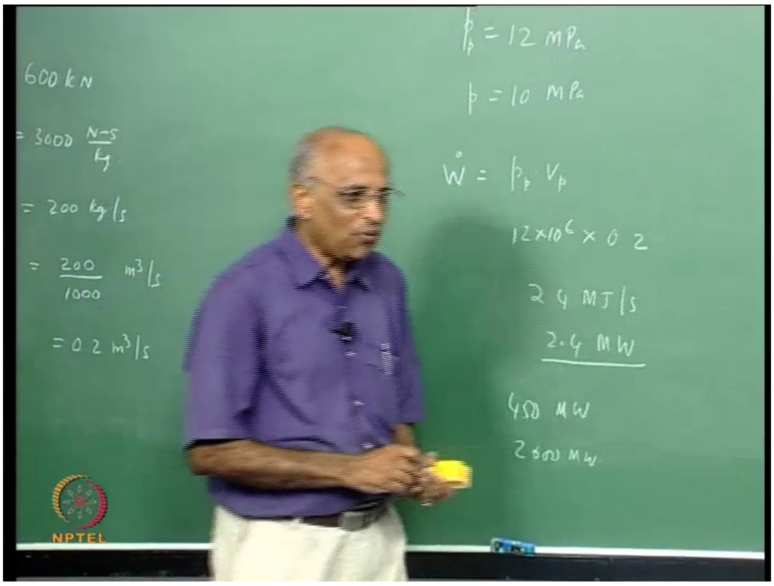

Because the chamber pressure I am talking of in terms of 100 bar the chamber pressure is 10 M P a, what is the work to be done by the pump which is to supply flow rate of point 2 meter cube per second at a pressure of 12 M P a. If we know has work done rate of work done is equal to P p into V p and this comes out to be let us calculate 12 into 10 to the power 6 into V p is 0.2 meter cube that is equal to 2.4 into mega Joule per second which is equal to so much Megawatts. Can we have some feel for this number? The power produce in the anode plant which supplies entire electricity to Chennai is something like 450 Megawatt. If we take a super thermal power plant like Ramagundam, it has something like 2400 or 2600 Megawatt. That means the power we are talking is enormous, I cannot have a battery or an electrical power which is doing it.

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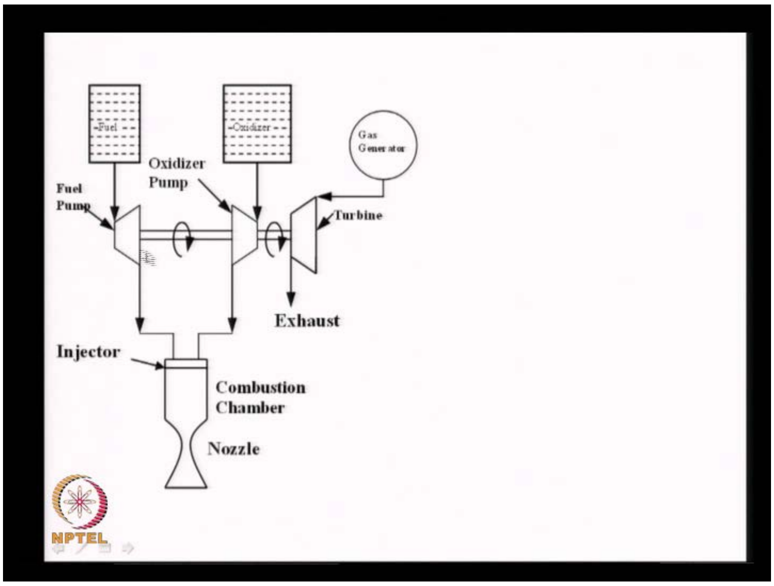

And therefore, what we normally do is, we need something like a gas generator which can supply work to a turbine and using the turbine I drive the time and therefore, it becomes a pump and a turbine and it is known as a turbo pump. I require another gas source, but to have a dedicated gas source is going to be a problem.

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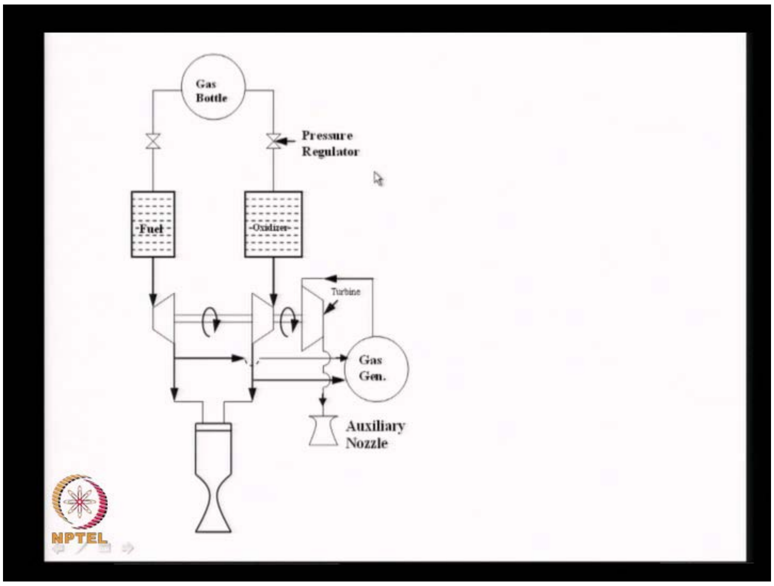

And therefore, what we do is we take the fuel, we take the oxidizer, we pump it into it. I remove some fuel from the fuel line, I remove some oxidizer from the line, I burn these gases separately over here, generate hot gases. Supply these hot gases into your turbine, generate work which drives the two fuel pump and oxidizer pump and supplies it to the chamber. And the exhaust from the turbine is left out this is an auxiliary nozzle, which means part of the fuel is used in generating high temperature gases, not very high because the turbine cannot take very high temperatures and therefore, you leave it to the ambient. And this becomes what is known as a gas generator cycle that means, I have a pump which is supplied gas through a gas generator and such type of a feed system is known as a gas generator cycle for feeding propellants.

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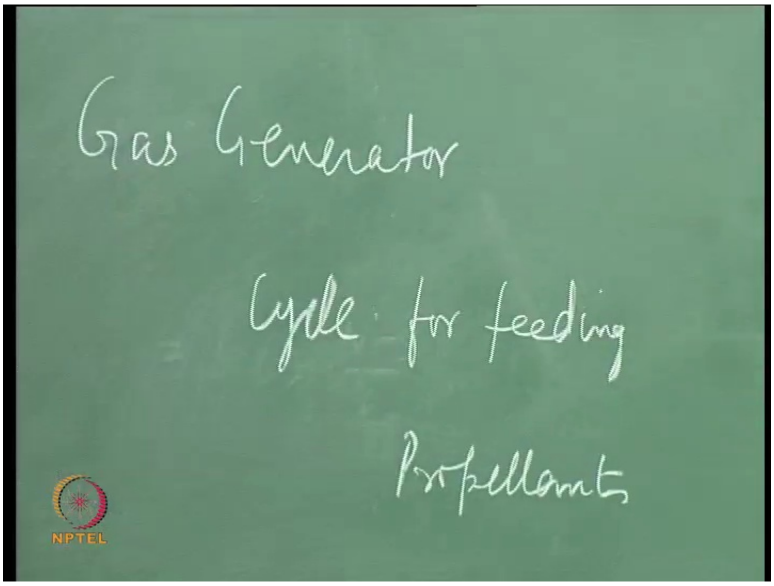

I think I will stop here, but all what we did in today’s class is we looked at that beetle, and said well a liquid propellant rocket is quite similar to that. We talked in terms of cold gas pressurization consisting of blow-down, regulated, may be hot gas pressurization, and then found may be when my duration of the rocket is little large and my thrust is large or my chamber pressure is large. The it is just not humanly possible to carry such huge masses of gas which are required. I need a pump, but then we found a pump demands huge amount of energy, I wanted a gas generator and this is what we call as a gas generator cycle. In the next class, we will advance ourselves we will see what are the other cycles which we can use and calculate, what is the performance of a rocket corresponding to those cycles? And in then we will go to the components of a rocket. Well, thank you. Then I think that is about it.